CHAPTER 4

COMPUTATION OF AVAILABLE TRANSFER CAPABILITY

4.1 INTRODUCTION

As discussed in the previous chapters, load flow study plays a vital role in operation and control of modern power systems. It can also be used for the computation of transfer capability. In a deregulated system, the information about the transfer capability will help the energy marketers in reserving the transmission services. For secured and economic supply of electric power, long distance bulk power transfers are essential, but the power transfer capability of a power system is limited. To operate the power systems safely and to gain the advantages of bulk power transfers, computations of transfer capability is essential. Transfer capability plays a vital role in liberalized electricity market. All the transmission lines are utilized significantly below their physical limits due to various constraints. By increasing the transfer capability the economic value of transmission lines can be improved and also there will be an increase in overall efficiency as more energy trading can take place between the competing regions operating with different price structures. The power system should be planned and operated such that these power transfers are within the limits of the system transfer capability.
Transfer capability of a power system is defined as the maximum power that can be transferred from one area to another area.

4.2 GENERAL MOTIVATION

In open access transmission system, the transmission network owners are required to provide unbundled services to support power transactions and to maintain reliable operation of the networks. In a liberalized electricity markets, to enforce the open access policy North American Energy Reliability Council (NERC) in conjunction with Federal Energy Regulatory Commission (FERC) defined the term available transfer capability (ATC) to be posted in open access same time information system (OASIS) to inform all the energy market participants of a power system. This information is required to be made available on hourly or daily basis. The two major challenges that make the task of ATC calculation of a nonlinear power system more challenging are computing speed and accuracy due to static and dynamic security constraints.

Deregulation of power market has imposed great impact on the utility industry. For smooth transaction of power between the areas or paths new technologies and computation methods are urgently needed. Transfer capability of a power system also indicates how much inter area power transfer can be increased without system security violations. The vital information required for the planning and operation of the large power systems can be obtained from these transfer capability
calculations. These details provide system bottlenecks to the planners and the limits of the power transfers to the system operators. The risk of overloads, equipment damage and unexpected blackouts can be reduced by repeated estimation of these transfer capabilities. These calculations also help to determine the quantity of lost generation that can be replaced by potential reserves and limiting constraints in each circumstance.

Due to the deregulation of power systems the power transfers are increasing which is necessary for a competitive market for electric power. There is a strong economic incentive to improve the accuracy and effectiveness of the transfer capability computations for the use by the power system operators and the power markets.

Transfer capability can be computed using different methods and these computations are evolving. The methods used at present are oversimplified and they do not consider the effects such as nonlinearities, system policies, interactions between the power transfers and loop flows. Under open access environment of power system actual evaluation of ATC is very much essential and a practical software package for computing ATC will be an important tool for all transmission providers. In recent years a significant progress has been made in developing such a tool, one remaining major challenge is to determine ATC accurately under varying load conditions considering static and dynamic security limits. The main objective of this research is to improve
the accuracy and incorporate the pragmatism in transfer capability computations.

4.3 DEFINITIONS

According to the report approved by NERC the definitions of ATC are as follows. Fig. 4.1 [64] represents the various terms.

**Total Transfer Capability (TTC):** It is defined as the quantity of electric power that can be transferred over the interconnected transmission path reliably without violating the predefined set of conditions of the system.

**Available Transfer Capability (ATC):** It is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. Mathematically, ATC is defined as the Total Transfer Capability (TTC) less the Transmission Reliability Margin (TRM), less the sum of existing transmission commitments (which includes retail customer service) and the Capacity Benefit Margin (CBM).

**Transmission Reliability Margin (TRM):** It is defined as that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.

**Capacity Benefit Margin (CBM)** is defined as that amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements.
4.4 TOTAL TRANSFER CAPABILITY

Total Transfer Capability (TTC) is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre- and post-contingency system conditions. The various constraints that limit Total Transfer Capability may be the physical and electrical characteristics of the systems including thermal, voltage, and stability limits as shown in Figure 4.2.

\[
\text{TTC} = \text{Minimum of \{Thermal Limit, Voltage Limit, Stability Limit\}}
\]

TTC is an important parameter that indicates how much power transfer can take place without compromising the system security. It provides vital information for the planners, operators and marketers. The accurate TTC calculation is essential to ensure that power system can...
operate without reliability risks. A number of methods exist for calculation of TTC and excessive conservative transfer capability may limit the transfer unnecessarily and also lead to inefficient operation of power system. In other words TTC is the maximum value of power transfer between the paths without any limit violations, with or without contingency. The objective can be defined as the determination of maximum real power transfer between the utilities.

![Fig. 4.2 Limits of total transfer capability](image)

Transfer capability can be calculated as follows

- Establish a base case which is assumed to be a secured operating condition so that all line flows and bus voltage magnitudes lie within their operating limits.

- Specify a transfer which includes source and sink powers.
• Establish a solved case by increasing source and sink powers until there is a limit violation.

• The transfer margin is the difference between the limiting case transfer and the base case transfer.

4.4.1 PURPOSE OF TRANSFER CAPABILITY COMPUTATIONS

The need for transfer capability computations:

• Estimation of TTC can be used as a rough indicator of relative system indicator.

• It can be used for comparing the relative merits of planned transmission betterments.

• To improve reliability and economic efficiency of the power markets.

• For providing a quantitative basis for assessing transmission reservations to facilitate energy markets.

4.5 METHODS OF TRANSFER CAPABILITY CALCULATION

A number of methods have been proposed in the literature. These methods are classified as i) continuation power flow (CP FLOW) [68] based methods ii) optimal power flow (OPF) based methods and iii) Linear approximation methods. Various methods of calculating transfer capability are explained below.
Continuation methods in which the transfer capability is computed using a software model called continuation. This process requires a series of load flow solutions to be solved and tested for limits.

Optimal power flow approach is another method to formulate an optimization problem. Equality constraints obtained from power flow are used in this approach.

Linear methods use PTDFs (power flow distribution factors) to express the percentage of power transfer that occurs on a transmission path.

4.5.1 CONTINUATION POWER FLOW APPROACH

Continuation power flow method is a comprehensive tool for tracing the steady state behavior of the power system due to parametric variation [84]. The parameters which are varied include bus real and/or reactive loads, area real and/or reactive loads and real power generations at generator or P-V buses. Continuation methods are also known as curve tracing or path following which are used to trace solution curves for general non-linear algebraic equations with a parametric variation. These methods have four basic elements:

- Parameterization: This is a mathematical way of identifying each solution for quantifying next solution or previous solution.
- Predictor: To find an approximate point for the next solution. Tangent or secant method is used for this purpose.
• Corrector: To correct error in an approximation produced by the predictor before it accumulates.

• Step size control: To adapt the step length for shaping the traced solution curve.

This method is based on the static model of the power system. Basically it calculates the successive equilibrium points for the Equation 4.1 assuming slow variation of the load parameter (λ) which represents the increment in load demand and power supplied by the system generators.

\[ 0 = g(y, \lambda) \]  \hspace{1cm} (4.1)

Rewriting the load flow equations the real and reactive power can be represented by equation 4.2 and 4.3

\[ P_{Gi}(\lambda) - P_{Li}(\lambda) = \sum_{j=1}^{n} V_j V_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \]  \hspace{1cm} (4.2)

\[ Q_{Gi}(\lambda) - Q_{Li}(\lambda) = \sum_{j=1}^{n} V_j V_j \left( G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij} \right) \]  \hspace{1cm} (4.3)

The increments of the generator active power and demands are given by

\[ P_{Gi}(\lambda) = P_{Gi0} \left( 1 + \lambda K_{Gi} \right) \]  \hspace{1cm} (4.4)

\[ P_{Li}(\lambda) = P_{Li0} \left( 1 + \lambda K_{Li} \right) \]  \hspace{1cm} (4.5)

\[ Q_{Li}(\lambda) = Q_{Li0} \left( 1 + \lambda K_{QLi} \right) \]  \hspace{1cm} (4.6)

In Equation 4.5 and Equation 4.6 \( P_{Li0} \) and \( Q_{Li0} \) represent the base case (\( \lambda = 0 \)) active and reactive powers of \( i^{th} \) bus.
\( P_{Gio} \) in equation 4.5 is the base case active power supplied by the generator of \( i^{th} \) bus.

\( K_{PLi} \) and \( K_{QLi} \) are coefficients defining the load power factors of the \( i^{th} \) bus.

\( K_{Gi} \) is a coefficient defining the generator participation factor in the \( i^{th} \) bus for certain loading level \( \lambda \).

Above equations can be written in a compact form as in equation 4.7.

\[
g(y, \lambda) = G(y) + \lambda d = 0 \tag{4.7}
\]

In above equation 4.7 \( d \) represents a vector indicating the direction of the active power increment supplied by the generators and reactive power increment consumed by the loads.

Successive solution of the above equation for different values of loading parameter \( \lambda \) is obtained by continuation power flow through a predictor and corrector [65, 66, 68] as shown in Figure 4.3.
4.5.2 OPTIMAL POWER FLOW APPROACH

The application of Optimal Power Flow (OPF) in power system congestion management has been studied by some researchers [69][70][71][72]. In the mean time, TTC calculation by OPF approach has been proposed since 1999 [73][74][75]. The basic concept of OPF approach is formulating the TTC calculation as an optimization problem, with equity constraints of power flow, inequality constraints from basic operation and equipment limits to more detailed approximation of transient stability security requirements. The objective function, obviously, is the maximum power flow on the specified transmission route. To determine the total transfer capability the objective is to
maximize the power transfer between the two areas subjected to the conditions that there is no voltage or thermal or stability limit violations. Total transfer capability problem formulation can be explained as follows.

Maximize

\[ P_i = \sum_{j \in i} P_{ij} \]  

(4.8)

Subjected to

\[ P_i - \sum_{j \in i} V_{ij} Y_{ij} \cos(\delta_i + \delta_j - \delta_j) = 0 \]  

(4.9)

\[ Q_i - \sum_{j \in i} V_{ij} Y_{ij} \sin(\delta_i + \delta_j - \delta_j) = 0 \]  

(4.10)

\[ P_{g \min} \leq P_g \leq P_{g \max} \]  

(4.11)

\[ Q_{g \min} \leq Q_g \leq Q_{g \max} \]  

(4.12)

\[ S_{ij} \leq S_{ij \max} \]  

(4.13)

\[ V_{i \min} \leq V_i \leq V_{i \max} \]  

(4.14)

4.5.3 REPEATED POWER FLOW APPROACH

Repeated power flow approach starts from a base case, and repeatedly solves the power flow equations each time increasing the power transfer by a small increment until an operation limit is reached [76]. The advantage of this approach is its simple implementation and the ease to take security constraints into consideration. In this dissertation, this method is adopted to solve TTC problem.
4.6 ALGORITHM FOR REPEATED POWER FLOW METHOD

In this research work, it is proposed to utilize the repeated power flow (RPF) method [67] for the calculation of transfer capabilities due to the ease of implementation. This method involves the solution of a base case, which is the initial system conditions, and then increasing the transfer. After each increase, another load flow is solved and the security constraints tested. Flow chart for the algorithm is given in Annexure IV. The computational procedure of this approach is as follows:

i. Establish and solve for a base case
ii. Select a transfer case
iii. Solve for the transfer case
iv. Increase step size if transfer is successful
v. Decrease step size if transfer is unsuccessful
vi. Repeat the procedure until minimum step size reached

4.7 AVAILABLE TRANSFER CAPABILITY [ATC]

Available transfer capability computations are essential for successful implementation of electric power deregulation where power producers and customers share a common transmission network for wheeling power from the point of generation to the point of consumption. The available transfer capability indicates the amount which inter-area bulk power transfers can be increased without compromising system security. The value used for available transfer capability affects both
system security and the profits made in bulk power transactions. Moreover, market participants can have conflicting interests in a higher or a lower available transfer capability. Thus under deregulation, there is increasing motivation for defensible calculations of available transfer capability.

4.7.1 IMPORTANCE OF ATC ASSESSMENT

In this present open access or deregulated environment all the participants (producers and buyers of electrical energy) desire to produce or consume large amounts of energy and may force the transmission system to operate beyond one or more transfer limits. This kind of operation leads to congestion of the system. Therefore accurate determination of available transfer capability is essential to ensure the system security and reliability while serving a wide range of bilateral and multilateral power transactions. The following reasons show the need of ATC computations

- It gives the amount of maximum additional power transfer between the specified interfaces.

- It ensures the secure operation of the system.

- On the basis of ATC computation firm and non-firm reservation of transmission services can be made.

- In a deregulated open access market it can be used as tool for transmission pricing.
• The limits or binding constraints for ATC can be used in power system planning and network expansion.

4.8 METHODS OF CALCULATING ATC

As explained above the following methods are used for determination of ATC

1. Load flow / continuous power flow (CPF) / Repeated Power Flow (RPF) methods.

2. Optimization based methods

3. Network sensitivity method

Full AC power flow method is the most accurate method for computation of ATC but its complexity can blot out relationships. The following linear methods are used for calculation of ATC. Transfer capabilities can be estimated with simple power system models such as the DC load flow approximation. A DC model may be preferable to an AC model particularly in circumstances where the extra data for an AC model is unavailable or very uncertain, such as the case of very long time frame analysis.

4.9 COMPUTATION OF ATC USING LINEAR METHODS

In this section linear methods are explained briefly for determination of available transfer capability followed by the merits and demerits of these approaches.
4.9.1 DC POWER FLOW METHOD

This model assumes that the voltage magnitudes are constant and only the angles of the complex bus voltage vary. It is also assumed that the transmission line has no resistance and therefore no losses. In addition to the speed of computation this method has other useful properties like linearity and super position.

The following Equation 4.15 explain DC power flow method

\[ P_{ij} = \frac{1}{x_{ij}} \left( \theta_i - \theta_j \right) \]  

(4.15)

Where

\( x_{ij} \) line inductive reactance
\( \theta_i \) phase angle at bus \( i \)
\( \theta_j \) phase angle at bus \( j \)

The total power flowing in to bus \( i \) is the algebraic sum of generation and demand at the bus called bus power injection given by Equation 4.16.

\[ P_i = \sum_j P_{ij} = \sum_j \frac{1}{x_{ij}} \left( \theta_i - \theta_j \right) \]  

(4.16)

This can be expressed in a matrix form by Equation 4.17

\[
\begin{bmatrix}
P_1 \\
\vdots \\
P_n
\end{bmatrix} = \begin{bmatrix} \mathbf{B} \end{bmatrix} \begin{bmatrix}
\theta_1 \\
\vdots \\
\theta_n
\end{bmatrix}
\]

(4.17)

Where the elements of susceptance matrix \( \mathbf{B} \) are functions of line reactance \( x_{ij} \).
Phase angle of one of the buses is set to zero and eliminating the row and column from B_x matrix, the reactance matrix can be obtained by inversion.

The phase angles are obtained as a function of bus injections as shown in Equation 4.18

\[
\begin{bmatrix}
\theta_1 \\
\vdots \\
\theta_{n-1}
\end{bmatrix} = \begin{bmatrix}
P_1 \\
\vdots \\
P_{n-1}
\end{bmatrix} X
\]

Line flows \( P_{ij} \) are obtained from Equation 4.16 to compare with the line MW limits.

**4.9.2 POWER TRANSFER DISTRIBUTION FACTORS**

According to power flow point of view power injected in to the system at a point by generator is extracted by a load at another point which is known as transaction. Transaction can be found from the linear property of DC load flow model using sensitivity factor PTDFs [78, 79]. Power transfer distribution factor (PTDF) is defined as the coefficient of the linear relationship between the amount of a transaction and the flow on a line. As it relates the amount of one change i.e. transaction amount to another change i.e. the lone flow. PTDF is the fraction of amount of a transaction from one zone to another over a specified transmission line. \( \text{PTDF}_{ij,mn} \) represents the fraction of a transaction from \( m \) zone to zone \( n \) that flows over a transmission line connecting zone \( i \) to zone \( j \).
The Power Transfer Distribution Factor (PTDF) is given by Equation 4.19

\[ PTDF_{ij,nn} = \frac{X_{im} - X_{jm} - X_{in} + X_{jn}}{x_{ij}} \]  

(4.19)

Where

- \( x_{ij} \) transmission line reactance connecting zone \( i \) and zone \( j \)
- \( X_{im} \) entry in the \( i^{th} \) row and \( m^{th} \) column of the bus reactance matrix \( X \)

The change in line flow associated with a new transaction is then given by Equation 4.20.

\[ \Delta P_{ij}^{New} = PTDF_{ij,nn} \cdot P_{nn}^{New} \]  

(4.20)

### 4.9.3 LINE OUTAGE DISTRIBUTION FACTORS (LODF)

The simple but most inaccurate method used to calculate the effect of line outage is DC power flow contingency. The speed of computation of this method can be improved by using another sensitivity called line outage distribution factor (LODF). When a line outage occurs in a system the power flowing on that line is redistributed on to the remaining lines in the system. This redistribution is measured by LODF and the fraction of power flowing on the line from zone \( r \) to zone \( s \) before it is removed which now flows over a line from zone \( i \) to zone \( j \) is given by \( LODF_{ij,rs} \).
The change in power flow is given by

\[ \Delta P_{ij,rs} = LODF_{ij,rs} \cdot P_{rs} \]  \hspace{1cm} (4.21)

\[ LODF_{ij,rs} = \frac{X_{ir} \cdot x_{ij}}{N_{ij} \cdot x_{ij}} \cdot \frac{N_{rs} \cdot x_{rs} - X_{ss} - 2X_{rs}}{N_{rs} \cdot x_{rs} - (X_{rr} + X_{ss} - 2X_{rs})} \]  \hspace{1cm} (4.22)

Where

- \( x_{ij} \) line reactance connecting zone \( i \) and \( j \)
- \( X_{ir} \) entry in the \( i^{th} \) row and \( r^{th} \) column of the bus reactance matrix
- \( X \)
- \( N_{ij} \) number of circuits connecting zone \( i \) and zone \( j \)

### 4.10 MAJOR ADVANTAGES & DISADVANTAGES OF THE EARLIER METHODS:

The advantages and disadvantages of various methods of transfer capability computation are as follows:

#### 4.10.1 DC APPROXIMATION

The DC approximation is preferred for these reasons:

- Fast computation - no iteration.

- Thermal limits, MW limits are considered.

- Network topology handled with simple and linear methods.

- Good approximation over large range of conditions.

  Minimum data is required.

But DC approximation is poor for these reasons:

- It cannot identify voltage limits
• It is not accurate when VAR flow and when voltage deviations are considerable.

• Over use of linear superposition increases errors

4.10.2 SENSITIVITY FACTORS

One of the earliest solutions proposed for Available Transfer capability (ATC) is sensitivity analysis. These sensitivity factors are based on linear incremental power flow, which are very simple to define and calculate.

This approach has a major disadvantage that they do not consider the nonlinear effects of voltage and reactive power. Moreover the methods based on Power Transfer Distribution Factors (PTDFs) and Line Outage Distribution Factors (LODFs) can be used to estimate the ATC of the cases nearer to the base case from which these factors are derived.

4.10.3 OPTIMAL POWER FLOW METHOD

Optimal Power Flow (OPF) and Security Constrained Optimal Power Flow (SCOPF) are widely used to determine ATC in power corridors of the system. However these optimization methods are suitable in case of open access system where there is a possibility of power transactions occurring from any point to any point.

4.10.4 CONTINUATION POWER FLOW

As discussed earlier this method is initially used for finding maximum loadability point, however its applications are extended to
determine TTC and ATC. The computational time increases due to its complexity, when contingencies are included.

**4.11 ATC COMPUTATION USING COMPLEX VALUED NEURAL NETWORKS**

The practical computations of transfer capability are evolving. The computations presently being implemented are usually oversimplified and in many cases do not take sufficient account of effects such as interactions between power transfers, loop flows, non-linearities, operating policies and most importantly voltage collapse blackouts. The transfer capability estimation method proposed by X. Luo et. al. [77] uses a Multi Layered Feed Forward Neural Networks which is capable of reflecting variations in load levels and in the status of generation and transmission lines. The transfer capability was estimated accurately of between system areas with variations in load levels, in the status of generation, and in the status of lines. In this work Quick prop algorithm is used to train the neural network.

The goal of the methods described here is to improve the accuracy and realism of transfer capability computations. The artificial neural network approach reported in the methods proposed require a large input vector for bilateral transaction, so it has oversimplified the determination of ATC by limiting it to a special case of power transfer to a single area from all of the remaining areas. Therefore, this method is unable to track down the bus-to-bus transactions, which is the true
spirit of deregulation and nonlinearities of the systems are also not considered.

4.11.1 ASSUMPTIONS

From the formulations discussed in section 3.4 a Complex Valued Neural Network approach is implemented for ATC computation.

The following assumptions are made while calculating the ATC.

a) The base case power flow of the system is feasible and corresponds to a stable operating point;

b) The load and generation patterns vary very slowly; and

c) TTC calculation is in the steady state analysis domain.

4.12 COMPUTATION OF ATC FOR A 9-BUS SYSTEM

For computing Available Transfer Capability using the proposed approach a 9 bus system [120] is considered (Annexure – 1). It has 3 generator buses and the number of transmission lines is 9 as shown in Figure 4.4.

This method involves the solution of a base case, which is the initial system conditions, and then increasing the transfer. After each increase, another load flow is solved and the security constraints tested. Voltage constraint is taken
The system divided in to two areas. Area 1 comprises of bus 1, bus 3, bus 4, bus 5 and bus 6 whereas area 2 comprises of the remaining buses as shown in Fig. 4.4 [84]. The tie lines between the two areas are line 4-9 and line 6-7. These lines transmit the power from one geographical area to other area.
4.12.1 LEARNING METHODOLOGY

Learning methodology uses complex back propagation algorithm explained in Chapter 3. Repeated power flow method is utilized to generate training patterns using Newton Raphson load flow method.

Repeated power flow (RPF) method is proposed for calculating ATC due to the ease of implementation. In this method the available transfer capability (ATC) from one bus/area/zone to another bus/area/zone can be found by varying the amount of transaction until one or more line flows in the transmission system considered or a bus voltage reaching the limiting value. The proposed new methodology is based on the full Ac load flow and strong generalization capability of complex neural network offers a great potential for real time evaluation of ATC incorporating load variation, effect of reactive power loss of the system.

For calculating ATC using Repeated Power Flow (RPF) method the following choices are made:

- Establish a secure, solved base case.
- Specify a transfer including source and sink assumptions.
- Identify the branch flows influencing the ATC of selected branch appreciably.
- Identify the line outages having significant influence on the above said branch power flows.
• Generate numerous training data sets involving above said power flows and line outages.

• The transfer margin is the difference between the transfer at the base case and the limiting case.

The flow chart for the above algorithm is shown in Annexure –IV.

The calculation of ATC is done by using the Newton Raphson load flow solution to compute the power flow of each transfer case. This method is less prone to divergence with ill-conditioned problems. And also the number of iterations required is independent of the system size. The loads at bus number 7 and 9 are increased simultaneously and the transfers from area 1 to area 2 are obtained. The total transfer capability is the sum of transfers through the interconnecting lines i.e. line joining buses 4 and 9, buses 6 and 7. The available transfer capability is given by Equation 4.23

\[
\text{ATC} = \text{TTC} - \text{base case transfer} \quad (4.23)
\]

Satisfying the following system operating conditions

\[
P_i - \sum_{j \in N} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) = 0 \quad (4.24)
\]

\[
Q_i - \sum_{j \in N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) = 0 \quad (4.25)
\]

\[
P_{g \text{ min}} \leq P_g \leq P_{g \text{ max}} \quad (4.26)
\]

\[
Q_{g \text{ min}} \leq Q_g \leq Q_{g \text{ max}} \quad (4.27)
\]

\[
V_{i \text{ min}} \leq V_i \leq V_{i \text{ max}} \quad (4.28)
\]
The above Figure 4.5 shows the P-V curve obtained from repeated power flow. The load in area 1 that is at bus 5 is maintained as 90+j30 where as the load in area 2 that is at bus 7 and bus 9 is varied slowly. It is assumed that bus 7 and bus 9 are critical buses compared to other buses and the voltage collapse points of these buses are shown with respect to the total load in area 2. From the results obtained from the repeated power flow it is observed that the voltage at these two buses reached the nose point compared to other buses.
Figure 4.6 represents the P-V curve without considering the contingencies. To show the effect of change of load in one area on the voltage profile these curves are plotted at different loads. In this case the load is taken as 120+j40 at bus 5 of area one.
Fig. 4.7 P-V curves with load 150+j50

In figure 4.7 variations in voltage is plotted at a different load of 150+j50 in area 1. It is observed that at a lesser value of the convergence is ceased as shown which will also affect the transfer capability of the system. It is observed that the there is an interaction between the power transfers and variation of load. It is also observed that there is a certain change the load margin due to which the transfer capability also changes.
**Fig. 4.8 P-V curves with line outage 4-5**

In Figure 4.8 the bus voltages at bus 7 and bus 9 are plotted using RPF method considering a single contingency with line outage 4-5. The load in area 1 is maintained at 90+j30. When compared with the Figure 4.7, for the same load in area 1 there is large change in load power margin and hence the transfer capability also. The graphical representation of change in ATC is shown in Fig. 4.10 and Fig. 4.11.
The single contingencies considered in Figure 4.9 is outage of line connecting bus 5 and bus 6 in area 1. It can be observed that the voltage collapse at bus 7 and bus 9 at a lower value of load compared to that of contingency free system.

**Fig. 4.9 P-V curves with line outage 5-6**
Figure 4.10 represents the variation of available transfer capability with respect to the change in load in area 1. The load in area 1 is changed with constant power factor. As the load is increased the ATC from area 1 to area 2 is decreased due to decrease in load margin. No contingencies are considered here.
Fig. 4.11 Effect of change in load on ATC with contingency

The variations in ATC with respect to the changes in load of area 1 with contingency i.e. removing line 4-9 are shown in Figure 4.11.

The number of training samples is 40 which are used for training the network. These training samples are obtained from repeated load flow method at different load patterns and two single line outages. The proposed network accepts the diagonal elements of bus admittance matrix to map the contingencies and load in area 1 as inputs, the available transfer capability in complex form is the output. This method is proposed for better prediction how a realistic power system will react.
over a wide range of operating conditions. The variation of error with respect to number of iterations is shown in Figure 4.12.

![Error plot](image)

**Figure 4.12 Error plot**

### 4.12.2 RESULTS AND DISCUSSIONS

For the purpose of verifying the validity and correctness of the proposed method a 9 bus system is selected to compute the real and reactive power transfer from one area to another area. The system consisting of 9 buses is divided in to two areas. The complex load levels
used to create data for training the proposed neural network in area 1 are varied from 100% to 250% of base case values using different line outages. The available transfer capability (ATC) in MW and the reactive power transfers in MVAR at different test cases are computed. The comparison between the proposed CVNN method and the repeated power flow (RPF) methods are shown in Tables 4.1 to 4.4.

**Table 4.1: Power transfer and ATC without contingency**

<table>
<thead>
<tr>
<th>Load in area 1</th>
<th>RPF</th>
<th>CVNN</th>
<th>ATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90+j30</td>
<td>438+j276</td>
<td>441+j282</td>
<td>441</td>
</tr>
<tr>
<td>120+j40</td>
<td>416+j245</td>
<td>418+j244</td>
<td>418</td>
</tr>
<tr>
<td>150+j50</td>
<td>393+j221</td>
<td>385+j224</td>
<td>385</td>
</tr>
<tr>
<td>180+j60</td>
<td>365+j190</td>
<td>359+j180</td>
<td>359</td>
</tr>
<tr>
<td>210+j70</td>
<td>340+j175</td>
<td>332+j168</td>
<td>332</td>
</tr>
</tbody>
</table>

**Table 4.2: Power transfer and ATC with Line 5-6 outage**

<table>
<thead>
<tr>
<th>Load in area 1</th>
<th>RPF</th>
<th>CVNN</th>
<th>ATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90+j30</td>
<td>357+j214</td>
<td>351+j211</td>
<td>351</td>
</tr>
<tr>
<td>120+j40</td>
<td>344+j203</td>
<td>338+j210</td>
<td>338</td>
</tr>
<tr>
<td>150+j50</td>
<td>323+j77</td>
<td>318+j95</td>
<td>318</td>
</tr>
<tr>
<td>180+j60</td>
<td>287+j130</td>
<td>284+j133</td>
<td>284</td>
</tr>
<tr>
<td>210+j70</td>
<td>210+j40</td>
<td>204+j42</td>
<td>204</td>
</tr>
</tbody>
</table>
### Table 4.3: Power transfer and ATC with Line 6-7 outage

<table>
<thead>
<tr>
<th>Load in area 1</th>
<th>RPF</th>
<th>CVNN</th>
<th>ATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90+j30</td>
<td>298+j192</td>
<td>290+j186</td>
<td>290</td>
</tr>
<tr>
<td>120+j40</td>
<td>293+j185</td>
<td>284+j182</td>
<td>284</td>
</tr>
<tr>
<td>150+j50</td>
<td>290+j186</td>
<td>281+j179</td>
<td>281</td>
</tr>
<tr>
<td>180+j60</td>
<td>282+j175</td>
<td>276+j172</td>
<td>276</td>
</tr>
<tr>
<td>210+j70</td>
<td>244+j260</td>
<td>239+j256</td>
<td>239</td>
</tr>
</tbody>
</table>

### Table 4.4: Power transfer and ATC with Line 9-4 outage

<table>
<thead>
<tr>
<th>Load in area 1</th>
<th>RPF</th>
<th>CVNN</th>
<th>ATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90+30j</td>
<td>90+j34</td>
<td>92+j35</td>
<td>92</td>
</tr>
<tr>
<td>120+j40</td>
<td>86+j38</td>
<td>86+j33</td>
<td>86</td>
</tr>
<tr>
<td>150+j50</td>
<td>80+j16</td>
<td>81+j20</td>
<td>81</td>
</tr>
<tr>
<td>180+j60</td>
<td>78+j20</td>
<td>76+j22</td>
<td>76</td>
</tr>
<tr>
<td>210+j70</td>
<td>73+j25</td>
<td>75+j21</td>
<td>75</td>
</tr>
</tbody>
</table>

It is observed that some outages cause a large change in power transactions as shown in Table 4.3 and Table 4.4. This is due to the voltage violation limits of the system. The results are compared and it is found that transfer capability is reduced by 70% in case of contingency.
4.13 COMPUTATION OF ATC FOR A 30 BUS SYSTEM

In this case IEEE 30 bus system Fig. 4.13 [77] (Annexure – 1) is considered for calculation of Available Transfer Capability. There are three areas which are interconnected through tie lines as shown in table 4.5 and 4.6.

<table>
<thead>
<tr>
<th>Area</th>
<th>Bus Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,2,3,4,5,6,7,8,9,11 &amp; 28</td>
</tr>
<tr>
<td>2</td>
<td>12,13,14,15,16,17,18,19,20 &amp; 23</td>
</tr>
<tr>
<td>3</td>
<td>10,21,22,24,25,26,27,29 &amp; 30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Areas</th>
<th>Tie Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1 – Area 2</td>
<td>Bus 4 – Bus 12</td>
</tr>
<tr>
<td>Area 1 – Area 3</td>
<td>Bus 6 – Bus 10</td>
</tr>
<tr>
<td></td>
<td>Bus 9 – Bus 10</td>
</tr>
<tr>
<td></td>
<td>Bus 28 – Bus 27</td>
</tr>
</tbody>
</table>

The power transferred between one area to other area is the sum of the powers transferred through the tie lines connecting the two areas. The available transfer capability between the areas can be found using the Equation 4.29. Repeated Power flow method discussed in section 4.10.2 is used to obtain the voltage constrained transfer capability of the system. The load in one area is varied in steps until Jacobian becomes singular and a point of voltage collapse is reached. In this case Bus 18, Bus 19 and Bus 20 are assumed to be critical buses according to voltage profiles and the P-V curves obtained from RPF solution are plotted.
Fig. 4.13 IEEE 30 Bus system
The voltage constrained transfer capability is calculated using repeated power flow (RPF). The voltages at bus 18, 19 and 20 are considered to be critical and the voltage collapse points are shown in Figure 4.14. The Load in area 3 is maintained at 48.5+j25 where as the load in area 2 is varied in small steps while the power factor is maintained constant at 0.8.
In the above Figure 4.15 the power factor maintained at 0.75 where as the area 3 load is changed to 210+j157.88. It can be observed that the voltage constrained total transfer capability is lesser compared to that with lesser power transaction.
The above Figure 4.16 shows the variation in bus voltages with the change in load of area 2 keeping the Area 3 load as 138.5+j103.8.

In this case the number of input patterns is reduced to two. The power factor of the load in area 2 and the load in area 3 are considered as inputs to observe the effect of load power factor in one area and change in real and reactive powers in another area.
The values of ATC estimated by using the load and power factor reduce the number of input neurons and very much useful for large systems. No contingencies are considered in this case. In case of contingencies the method used in the previous section can be used.

**Table 4.7: ATC with varying Load in area 3**

<table>
<thead>
<tr>
<th>P.F</th>
<th>Load in Area 3</th>
<th>ATC(_{1-2}) (RPF)</th>
<th>ATC(_{1-2}) (CVNN)</th>
<th>ATC(_{1-3}) (RPF)</th>
<th>ATC(_{1-3}) (CVNN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>138.5+j103.8</td>
<td>149</td>
<td>152</td>
<td>250</td>
<td>245</td>
</tr>
<tr>
<td>0.8</td>
<td>168.5+j126.3</td>
<td>151</td>
<td>150</td>
<td>260</td>
<td>258</td>
</tr>
<tr>
<td>0.8</td>
<td>198.5+j148.8</td>
<td>152</td>
<td>145</td>
<td>265</td>
<td>267</td>
</tr>
<tr>
<td>0.8</td>
<td>210.5+j157.8</td>
<td>151</td>
<td>144</td>
<td>268</td>
<td>270</td>
</tr>
</tbody>
</table>

In Table 4.7 The effect of change in load i.e. real and reactive power in area 3 on the transfer capability is shown. It is observed that the increase in load has a noticeable effect on the available transfer capability from area 1 to 2 and also from area 1 to 3. In this case the power factor is maintained constant while the load is varied in steps.

**Table 4.8: ATC with constant Load in area 3 and variable P.F**

<table>
<thead>
<tr>
<th>P.F</th>
<th>Load in Area 3</th>
<th>ATC(_{1-2}) (RPF)</th>
<th>ATC(_{1-2}) (CVNN)</th>
<th>ATC(_{1-3}) (RPF)</th>
<th>ATC(_{1-3}) (CVNN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.78</td>
<td>210.5+j157.8</td>
<td>150</td>
<td>148</td>
<td>267</td>
<td>272</td>
</tr>
<tr>
<td>0.8</td>
<td>210.5+j157.8</td>
<td>152</td>
<td>150</td>
<td>271</td>
<td>274</td>
</tr>
<tr>
<td>0.82</td>
<td>210.5+j157.8</td>
<td>153</td>
<td>150</td>
<td>274</td>
<td>278</td>
</tr>
<tr>
<td>0.86</td>
<td>210.5+j157.8</td>
<td>153</td>
<td>152</td>
<td>277</td>
<td>278</td>
</tr>
</tbody>
</table>
Table 4.8 shows the variation of ATC with respect to power factor and at a constant area load. There is a very small effect on ATC in this case. The result obtained using the proposed method is compared with the standard RPF method.

4.14 CONCLUSIONS

This chapter introduces the application of complex valued neural network for ATC computations with and without contingencies. To evaluate the performance a numerical example of 9 bus test system is presented. The voltage limits of the buses and the line losses are well considered in this method. It is observed that, using this method available transfer capabilities between system areas can be estimated accurately with variations in load levels, in the status of lines. The simulation results show that the proposed method is very effective in determining the ATC. The suitability of this method is also demonstrated by taking IEEE 30 bus system where the number of inputs are reduced to allow the on line computations of ATC for a larger system. In this problem it is observed that as the number of inputs mapping the nonlinear system output decreases the relative error increases. In a deregulated environment, the power transaction between one area to other area can occur only when there is adequate ATC available for that interface to ensure system security. This available transfer capability (ATC) information is to be continuously updated and made available to
all participants of the energy market through Open Access Same Time Information System (OASIS). For such type of n line applications the proposed method is suitable as it makes use of repeated power flow method based on Newton-Raphson formulation and the good generalization capability of the complex valued artificial neural networks.

The main conclusions of this work are:

- The proposed CVNN method is effective in calculating the ATC between different areas subject to system operating limits;
- This method can be adopted for computation of ATC with constant load power factor at different power factors of the load; and
- The application of proposed method can also be extended to determine the variations in ATC with respect to reactive power incorporating FACTS devices.