CHAPTER 5

DIFFERENTIAL EVOLUTION FOR AVAILABLE TRANSFER CAPABILITY IN THE PRESENCE OF WIND TURBINE GENERATOR

5.1 INTRODUCTION

In recent years, environmental concerns on global warming and local pollution have led to many countries and regions to promote renewable energy sources as means of meeting emission selection targets. Wind power is fast growing and most promising one among all renewable energy. The increasing level of wind generation connected to electrical grids has emphasized the necessity to carry out specific studies concerning the impact of wind generation on power system. In the previous chapters ATC estimation is evaluated with conventional synchronous generators alone. In this chapter the estimation of ATC incorporating the wind generation using Differential Evolution algorithm is discussed. Differential Evolution with self-tuned parameters is proposed for ATC estimation. DE/rand SF/1/bin scheme is used for the problem in which the mutation scheme uses randomly selected vector and only one weighted difference vector is used to perturb it. The mutation scheme is combined with binominal type crossover and with random scale vector. Convergence speed, simplicity and robustness by the evolutionary technique to reach the optimal solutions make suitable for large scale optimization problem like ATC estimation. The effectiveness of the proposed
5.2 MODEL OF WIND FARM

The power flow model for a fixed-speed wind turbine generator unit (FSWTGU) is developed to calculate the injected wind power of the FSWTGU system. In the case of a grid-connected induction generator, the induction machine injects/delivers active power to the grid and draws/absorbs reactive power from the grid. In that case, capacitors are sometimes connected to improve power factor and reduce losses. Here the RX model of wind farm with slip factor as one is considered as a PQ bus, which is the steady-state model of a generator, as shown in Figure 5.1.

![Figure 5.1 Induction machines steady-state model](Source: Andres Feijoo & Jose Cidras 2000)

The conservation of complex power theorem (Boucherot’s theorem) is applied in the model to write the following expression (Andres Feijoo & Jose Cidras 2000) for reactive power consumption of the wind farm.
Where

\[ V \] is the rated voltage,

\[ P \] is the real power (positive when injected into the grid),

\[ X \] is the sum of the stator and rotor leakage reactance,

\[ X_c \] is the resistance of the capacitors bank, and

\[ R \] is the sum of the stator and rotor resistances.

The following expression is (Andres Feijoo & Jose Cidras 2000) for the calculation of real power of the FSWTGU:

\[ P = \frac{1}{2} \rho AU^3 C_p \]  \hspace{1cm} (5.3)

where \( A \) is the rotor area, \( \rho \) the density of air, \( U \) is the wind speed, and \( C_p \) is the power coefficient. The above Equations (5.1 to 5.3) are introduced only to inject fixed wind power into the system. After wind turbines are connected to power system and a group of balance equations should be added to original power flow equations. The nominal parameters of Induction generators in wind farms are stator resistance is 0.00708\( \pi \), the rotor resistance is 0.00759\( \pi \) the stator reactance is 0.07620\( \pi \), the rotor reactance is 0.23289\( \pi \) and the value of mutual and capacitive reactance are 3.44979\( \pi \). since the intention of the model is to avoid high consumption of reactive power, hence the capacitive reactance and mutual reactance are assumed to be equal \( X_c = X_M \).
5.3 PROBLEM FORMULATION

ATC is defined as the additional power that can be transmitted through a specified interface over and above the already committed transactions. The problem of ATC computation in bilateral transaction can be formulated as an optimization problem in which the objective is to maximize the difference between TTC and ETC without violating the static constraints.

This is stated as

Maximize \( \text{ATC} = P_{Di}^{\text{new}} - P_{Di}^{\text{old}} \), \( \forall i \in t_k \) \hspace{1cm} (5.4)

where,

\( P_{Di} \) is the maximum transfer load at the ith bus,

\( P_{Di}^{0} \) is the base case load

\( t_k \) is the total number of transactions.

Subject to a set of system constraints as given below, where, \( P_{Di} \) is the maximum transfer load at the ith bus, \( P_{Di}^{0} \) is the base case load and \( t_k \) is the total number of transactions.

(a) Equality Constraints:

These include real and reactive power balance equations after incorporating the wind turbine generator at each node which can be written as,

Real power balance equation
\[ P_{Gi} + P_{WG} - P_{Di} - V_i \sum_{j=1}^{N_B} V_j \left[ G_{ij} \cos \theta_{ij} - B_{ij} \sin \theta_{ij} \right] = 0, \]

where \( i = 1, 2, ..., N_{B-1} \) \hspace{1cm} (5.6)

Reactive power balance equation

\[ Q_{Gi} - Q_{WG} - Q_{Di} - V_i \sum_{j=1}^{N_B} V_j \left[ G_{ij} \sin \theta_{ij} - B_{ij} \sin \theta_{ij} \right] = 0 \]

where \( i = 1, 2, ..., N_{PQ} \) \hspace{1cm} (5.7)

where

- \( G_{ij}, B_{ij} \) - Conductance and Susceptance of transmission line
- \( P_{Gi}, Q_{Gi} \) - Real and Reactive power generation of \( i^{th} \) bus
- \( P_{WG}, Q_{WG} \) - Real and Reactive power wind generator
- \( V_i \) - Voltage magnitude at bus-i
- \( N_{B-1} \) - Total number of buses excluding slack bus
- \( N_{PQ} \) - Total number of load buses
- \( \theta_{ij} \) - Voltage angle difference between bus-i and bus-j

(b) Inequality Constraints

These include system operating limits as given below,

Real and reactive power generation limit: These represent the minimum and maximum limit on the real and reactive power output of the generators.

\[ P_{gi}^{\text{min}} \leq P_{gi} \leq P_{gi}^{\text{max}}, \forall i \in n_g \]
\[
Q_{gi}^{\text{min}} \leq Q_{gi} \leq Q_{gi}^{\text{max}}, \forall i \in n_g
\]

**Voltage Limit:** This includes the upper and lower limits on the bus voltage magnitude at all the buses

\[
V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}} \quad \forall i \in n
\]

Where

\[V_i^{\text{min}}\text{ and } V_i^{\text{max}} - \text{Maximum and minimum of voltage limit}\]

**Line flow limit:** This constraint represents that the power flow in any line must be within its maximum permissible limit.

\[
S_{ij}^{\text{min}} \leq S_{ij} \leq S_{ij}^{\text{max}} \quad \forall l \in n_l
\]

where

\[S_{ij}^{\text{min}}\text{ and } S_{ij}^{\text{max}} - \text{Maximum and minimum limits of apparent power flow}\]

### 5.4 DIFFERENTIAL EVOLUTION

In 1995, Price and Storn proposed a new floating point encoded evolutionary algorithm for global optimization and named it DE owing to a special kind of differential operator which they invoked to create new offspring from parent chromosomes instead of classical crossover and mutation. Easy methods of implementation and minimum parameter tuning made the algorithm popular very soon. The optimization variables are represented as floating point numbers in the DE population. It starts to explore the search space by randomly choosing the initial candidate solutions within the boundary. Differential Evolution creates new offspring by generating a noisy each individual of the population. The different DE schemes involved are described as DE/x/y. DE stands for Differential Evolution, x represents a
string denoting the type of the replica of vector to be perturbed (whether it is randomly selected or it is the best vector in the population with respect to fitness value) and \( y \) is the number of difference vectors considered for perturbation of \( x \).

### 5.4.1 Population Initialization

The first step of DE optimization process is initialization of population. In initialization process all candidates are randomly generated as a real valued number within its corresponding feasible bounds using the expression

\[
X_{ij}^G = X_{i\text{min}} + \text{rand}_{[0,1]}^i \cdot (X_{i\text{max}} - X_{i\text{min}}), \quad i=1,\ldots,D \quad \text{and} \quad j=1,\ldots,NP
\]  

(5.8)

where, \( NP \) is number of population and \( D \) is number of decision parameter of the problem. \( X_{i\text{min}} \) and \( X_{i\text{max}} \) are the lower and upper bounds of the \( i^{\text{th}} \) decision parameter, respectively. \( \text{rand}_i[0,1] \) represents a uniformly distributed random value in the range \([0,1]\). Once every vector of the population has been initialised, its corresponding fitness value is calculated and stored for future reference.

### 5.4.2 Difference Vector based Mutation

During mutation, three random vectors are selected from current population. The mutation is carried out on randomly selected vector \( X_{r1}^G \) with the difference of two other randomly selected vectors \( X_{r2}^G \) and \( X_{r3}^G \). The mutation vector is generated using the Equation (5.9)

\[
V_i^G = X_{r1}^G + F \cdot (X_{r2}^G - X_{r3}^G)
\]  

(5.9)

where,
F is scaling factor, which is typically chosen from within the range [0, 1].

### 5.4.3 Binomial Crossover

The next step of DE optimization process is crossover. In this step, by applying crossover operation between target vector and mutant vector a trial vector $U_i^{(G)}$ is created according to a selected probability distribution

$$U_i^{(G)} = U_{j,d}^{(G)} = \begin{cases} V_{j,d}^{(G)} & \text{if } rand_j(0,1) \leq CR \text{ or } j = s \\ X_{j,d} & \text{otherwise} \end{cases} \quad (5.10)$$

The crossover constant $CR$ is a user-defined value (known as the “crossover probability”), which is usually selected from within the range [0, 1]. The crossover constant controls the diversity of the population and aids the algorithm to escape from local optima. $rand_j$ is a uniformly distributed random number within the range (0, 1). $s$ is the trial parameter with randomly chosen index \{1, ..., D\}, which ensures that the trial vector gets at least one parameter from the mutant vector.

### 5.4.4 Selection

Selection is final operation of DE procedure. This operator compares the fitness of the trial vector and the corresponding target vector and selects the one that provides the better solution. This selected vector is then treated as target vector for next generation.

$$X_i^{(G+1)} = \begin{cases} U_i^{(G)} & \text{if } f(U_i^{(G)}) \leq f(X_i^{(G)}) \\ X_i^{(G)} & \text{otherwise} \end{cases} \quad (5.11)$$
The feature of DE selection scheme is that a trial vector is compared with only one individual, not all the individuals in the current population.

5.5 IMPLEMENTATION OF DIFFERENTIAL EVOLUTION FOR TRANSFER CAPABILITY PROBLEM

The following issues are addressed in the implementation of differential evolution in ATC problem.

5.5.1 Issues to be Addressed

While applying DE for solving the ATC problem with wind generation, the following issues need to be addressed:

- Representation of the decision variables
- Formation of the Fitness function

5.5.2 Problem Representation

Implementation of DE for a problem starts with parameter encoding (i.e., the representation of the problem). Each individual in the differential population represents a candidate solution. The elements of that solution consist of all the decision variables in the system. For calculating ATC, the change in new load demand of sink bus value ($P_{Di^{new}}$), the location of wind turbine generator (WTG) and the value of WTG are taken as decision variable. The lower and upper bound for decision variable are taken as 1, ($ATC_{max}$) respectively. This bound may vary for different transactions. The solution variables are represented as floating point numbers and integers. With direct representation of the solution variables, the computer memory required to store the population is reduced.
5.5.3 Evaluation of Fitness Function

In the ATC estimation problem under consideration, the objective function comprises of Maximization of ATC with the incorporation of wind energy, satisfying the equality and inequality constraints. For each individual the equality constraints are satisfied by running the Newton Raphson power flow algorithm. The inequality constraints on the control variables are taken into account in the problem representation itself. Evaluation of the individuals in the population is accomplished by calculating the objective function value for the problem using the parameter set. The result of the objective function calculation is used to calculate the fitness value of the individual. Fitter chromosomes have higher probabilities of being selected for the next generation. The fitness function is given by

\[ F = P_{Di}^{new} - P_{Di}^{old} \]  

(5.12)

5.6 Algorithm for ATC Evaluation

The proposed DE solution for ATC problem is composed of the following steps:

1. Read bus data, generator data, branch data and Specify the transaction for which the ATC has to be computed.
2. Read data for DE operations i.e. maximum generation limit, number of population, the change in new load demand of sink bus value as the decision Variable, lower and upper limit of decision variable, scaling factor F and Crossover rate.
3. Set Generation Gen=0.
4. Generate population randomly according to Equation (5.8), where decision variable is within its feasible bound.
5. Compute ATC using Equation (5.1) for each population of parent vector

6. Initialize the iteration iter=1

7. For each iteration do the following steps
   a. Set the parent population with the maximum value $P_{Di}^{new}$ is the target vector $i$
   b. Perform mutation and crossover according to Equation (5.9) and (5.10) and get trial vector.
   c. Selection among the target and trial vector for the survival using Equation (5.11).
   d. Using selected best vector value run NR load flow and compute ATC.
   e. Check for any operating limit violation.
   f. If any limit is violated increase the iteration iter=iter+1, repeat again from step (b), till the process gets converged. If does not converge the population has reinitialized automatically, otherwise go to next step.
   g. Best vector selected will be the next parent vector for the next Population.

8. Increment the generation gen=gen+1

9. Check the maximum generation limit, if yes go to next step, otherwise go to step 4

10. Print the corresponding selected best vector as the optimum value of $P_{Di}^{new}$.

11. Compute ATC using Equation (5.1), and Print optimized values of ATC, position and values of WTG. The same is represented as flow chart in Figure 5.2.
Figure 5.2 Flow chart for ATC calculation using DE
5.7 SIMULATION RESULT

5.7.1 Test System

This section presents the details of the simulation study carried out on IEEE 24-RTS and IEEE 118 bus system for ATC computation with Wind plant under normal operating condition using the proposed approach. The reactive power demand at load bus is assumed to be increasing as a percentage of real power increase. The simulation studies were carried out by developing MATLAB program and by using Mat power 4.1 software.

5.7.2 ATC Estimation incorporating wind in IEEE 24-RTS Bus System

IEEE RTS 24 bus system consists of 11 generator buses, 13 load buses and 38 transmission lines. There are 6 frequently occurring transactions including 5 bilateral and one multilateral transaction which have been considered for ATC determination. Transaction T1 is between seller bus 23 and buyer bus-3. Multilateral transaction T6 is between seller buses 23 and 15 and buyer buses 10 and 3. The seller buses 23 and 15 share the increase in load of buyer buses in the ratio of 0.6 and 0.4 respectively. The details of different transaction are given in Table 5.1.

Estimation of ATC comprising WTG can be observed by different combination of market structures comprising bilateral and multilateral contracts. The WTG is modeled as an Induction generator and it is to be placed in load bus. Installation of WTG is accommodated as supplying of real and consumption of reactive power at the load bus.

For different transactions of market structures comprising bilateral and multilateral frequently occurring contracts, estimation of ATC is determined with the incorporation of wind generator modeled as PQ bus, with static limits intact.
Table 5.1 Transaction for IEEE 24-RTS bus system

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Source-sink</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>23-3</td>
</tr>
<tr>
<td>T2</td>
<td>23-10</td>
</tr>
<tr>
<td>T3</td>
<td>18-5</td>
</tr>
<tr>
<td>T4</td>
<td>22-9</td>
</tr>
<tr>
<td>T5</td>
<td>18-9</td>
</tr>
<tr>
<td>T6</td>
<td>23,10 (0.6,0.4)-15,3(0.6,0.4)</td>
</tr>
</tbody>
</table>

The size of the wind generator is taken as 5 MW. The value of Q calculated from Equation (5.2) will be injected into the system, incorporating the design parameters, and the corresponding value of real power to be withdrawn from the system, where the location of wind generator is calculated from the DE algorithm. The control parameters for the best result of DE for the above transactions are: No. of generations: 50; Population Size: 100; Decision variable: 1; Crossover probability: 0.5; Mutation probability: 0.7.

Table 5.2 ATC Estimation for IEEE 24-RTS bus system incorporating WTG of size (0-5MW)

<table>
<thead>
<tr>
<th>Transaction</th>
<th>ATC (MW)</th>
<th>ATC with WTG (MW)</th>
<th>% Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>23-3</td>
<td>118.5</td>
<td>179.7067</td>
<td>No Impact</td>
</tr>
<tr>
<td>23-10</td>
<td>385.5</td>
<td>531.2610</td>
<td>27.43</td>
</tr>
<tr>
<td>18-5</td>
<td>219</td>
<td>250.0176</td>
<td>12.404</td>
</tr>
<tr>
<td>22-9</td>
<td>281.9</td>
<td>373.061</td>
<td>24.43</td>
</tr>
<tr>
<td>18-9</td>
<td>289.15</td>
<td>345.7185</td>
<td>16.362</td>
</tr>
<tr>
<td>23,10 (0.6,0.4)-15,3(0.6,0.4)</td>
<td>428.60</td>
<td>512.760</td>
<td>16.413</td>
</tr>
</tbody>
</table>
Table 5.2 gives the impact of WTG in estimation of ATC and the same is compare with the values of ATC without wind.

The optimal location and optimal values of wind generator for various transactions are given in Table 5.3.

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Optimal WTG (MW)</th>
<th>Optimal location</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>3.3382</td>
<td>10</td>
</tr>
<tr>
<td>T2</td>
<td>1.1046</td>
<td>4</td>
</tr>
<tr>
<td>T3</td>
<td>2.7077</td>
<td>5</td>
</tr>
<tr>
<td>T4</td>
<td>4.5797</td>
<td>5</td>
</tr>
<tr>
<td>T5</td>
<td>3.4409</td>
<td>11</td>
</tr>
<tr>
<td>T6</td>
<td>4.2212</td>
<td>4</td>
</tr>
</tbody>
</table>

The Figure 5.3 is the comparison chart for various transaction of Enhanced ATC with wind modeled as load bus.

![Figure 5.3 Comparison of ATC for 24-RTS bus system with and without WTG.](image)
5.7.3 ATC Estimation Incorporating Wind in IEEE 118 Bus Systems

The IEEE 118-bus test system is used to demonstrate the feasibility of the proposed model for normal case. It has 54 generator buses and 186 transmission lines. The line rating of the transmission line is given in Appendix 2. All other data are the same as the standard IEEE 118-bus data (1996). ATC, for this system, has been determined for five bilateral transactions and a multilateral transaction. The Transaction details are given in Table 5.4. Multilateral transaction T6 is between seller buses 5 and 6 and buyer buses 40 and 60. The seller buses 72 and 80 share the increase in load of buyer buses in the ratio of 0.6 and 0.4 respectively. The ATC between any transmission interfaces is a function of network topology, generation dispatch and customer demand level. It is mostly affected by the real and reactive power loads.

### Table 5.4 Transaction details for IEEE 118 bus system

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Source-sink</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>32-75</td>
</tr>
<tr>
<td>T2</td>
<td>12-60</td>
</tr>
<tr>
<td>T3</td>
<td>24-40</td>
</tr>
<tr>
<td>T4</td>
<td>65-100</td>
</tr>
<tr>
<td>T5</td>
<td>46-80</td>
</tr>
<tr>
<td>T6</td>
<td>5,6 (0.6,0.4)-40,60(0.6,0.4)</td>
</tr>
</tbody>
</table>

Comparing the ATC values from Table 5.5 it can be seen that after incorporating WTG to the load bus optimally by Differential Algorithm there are changes in each point-to-point ATC, some point to point ATC do not have obvious changes such as in transaction 65-100 where the ATC changes from 499.35MW to 500.0117 MW, this is because these load nodes are far away from the load nodes including wind generators.
Table 5.5  Optimal location and Capacity of WTG (0-10 MW) for IEEE 118 bus system

<table>
<thead>
<tr>
<th>Transaction</th>
<th>ATC (MW)</th>
<th>ATC with WTG (MW)</th>
<th>Improvement in ATC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-75</td>
<td>151.05</td>
<td>209.0029</td>
<td>27.73</td>
</tr>
<tr>
<td>12-60</td>
<td>254.34</td>
<td>750.0059</td>
<td>66.133</td>
</tr>
<tr>
<td>24-40</td>
<td>239.05</td>
<td>311.5396</td>
<td>23.26</td>
</tr>
<tr>
<td>65-100</td>
<td>499.35</td>
<td>500.0117</td>
<td>NC</td>
</tr>
<tr>
<td>46-80</td>
<td>527.85</td>
<td>570.3226</td>
<td>7.4466</td>
</tr>
<tr>
<td>5,6 (0.6,0.4)-40,60 (0.6,0.4)</td>
<td>587.05</td>
<td>635.42</td>
<td>7.6122</td>
</tr>
</tbody>
</table>

The control parameters for the best result of DE for the above transactions are: No. of generations: 100; Population Size: 50; Decision variable: 1; Crossover probability: 0.5; Mutation probability: 0.7. The convergence characteristics of DE for transaction T2 of IEEE 24-RTS bus system is shown in Figure 5.4. The converged ATC value is 750.0059 which is the maximum ATC value in p.u for the corresponding optimal wind Generator bus and its location. It was clearly shown that there is no appreciable change in fitness value after 20 generations.

Figure 5.4  Convergence of the DE-ATC algorithm for Transaction T2 for IEEE 118 bus system with wind generator
The optimal location and optimal values of wind generator for various transactions are given in Table 5.6.

Table 5.6  ATC Estimation for IEEE 118 bus system incorporating WTG of size (0-10MW)

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Optimal WTG ( MW)</th>
<th>Optimal location</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>5.1222</td>
<td>67</td>
</tr>
<tr>
<td>T2</td>
<td>9.9316</td>
<td>16</td>
</tr>
<tr>
<td>T3</td>
<td>7.7810</td>
<td>17</td>
</tr>
<tr>
<td>T4</td>
<td>9.2864</td>
<td>101</td>
</tr>
<tr>
<td>T5</td>
<td>7.1750</td>
<td>96</td>
</tr>
<tr>
<td>T6</td>
<td>7.7810</td>
<td>88</td>
</tr>
</tbody>
</table>

The Figure 5.5 is the comparison chart for various transaction of Enhanced ATC with wind modeled as load bus. From the figure it is inferred that impact of ATC is done by incorporating the PQ wind model in the system.

![Figure 5.5](chart.png)  

Figure 5.5  Comparison of ATC for IEEE 118 bus system with and without WTG.
5.8 SUMMARY

In this chapter, incorporating wind generator as PQ bus in the test bus systems and the effects are measured. From technical point of view, less generation of wind generator has been chosen. Evolutionary algorithm with and without wind generator have been applied and the obtained results are compared. The optimal capacity of the wind generator and its location has been computed using DE to maximize the ATC in the system for particular transaction. The test results on IEEE-24 RTS and IEEE 118 bus system shows the proposed method is applicable and able to determine ATC limited by thermal and bus voltage limit. The analysis clearly indicates the estimation of ATC. The present concept has better applicability for utilizing renewable sources in a deregulated environment for ATC Estimation for normal system.