Coordinated generation and transmission expansion planning approach considering probabilistic available transfer capability

Ping Zhou¹, Peng Kang², Ruiguo Chen¹, Hao Tian¹,
¹. State Grid Chongqing Electric Economic Research institute, Chongqing 400000, China;
². State Grid Chongqing, Tsinghua University, Chongqing 400000, China

153326062@qq.com; kp@cq.sgcc.com.cn; chenruiguo@cq.sgcc.com.cn; tianhao5@cq.sgcc.com.cn

Abstract. The available transmission capacity of the network has a great impact on the safety and reliability of the whole system. After the reform of electricity market, the grid is required to have the highest available transmission capacity (ATC) based on the existing load due to the uncertain factors. Therefore, it is necessary to consider the growing demand for available transmission capacity from the grid planning stage. Meanwhile, considering the uncertain factors have a great influence on the available transmission capacity (ATC), this paper first models the three uncertain factors and introduces the solving method of probabilistic available transfer capability, then proposes a grid expansion planning model considering the probabilistic available transmission capacity under the influence of uncertainties, which is applied to the six-node test system. Finally, the genetic algorithm is used to solve the final planning scheme. Compared with other planning schemes, this method can consider the comprehensive investment cost and the probability available transmission capacity. The case study shows that the method is effective and can achieve good results.

1. Introduction
The power market reform has become a trend in the development of the power industry in the world by breaking the traditional top-down, monopolistic power system management model, deregulating and introducing competition mechanisms to achieve optimal allocation of resources and improve the efficiency of power system operation. In this context, the calculation of existing transmission capacity becomes a necessary prerequisite for power market participants to complete power transactions [1]-[4]. The North American Electric Reliability Council (NERC) gives the definition of available transmission capacity (ATC) [5]: ATC refers to the remaining transmission capacity available for commercial use on the actual physical transmission network based on the existing transmission contract. In the traditional vertical control environment, the transmission capacity between regions is only a reference information. However, in the power market environment, the system operation uncertainty increases, the energy transaction changes rapidly, and the probability of failure will also increase. Therefore, it is necessary to study the available transfer capability (ATC) to improve the utilization rate of the power grid and optimize the grid structure. It can also provide important reference information for grid planning and operation.
At the same time, from the perspective of the power company itself, it is required that the power grid has the highest possible technical adaptability to the future external environment, and has the highest available transmission capacity on the basis of the existing load, that is, for all possible values of external factors that affect the available transmission capacity of the grid, the planning scheme should have sufficient capability to “disregard” their existence, that is, have sufficient ability to “eliminate” the uncertainty. This requires the available transmission capacity of the planning scheme to be as large as possible.

The calculation methods of ATC can be roughly divided into deterministic calculation methods and probabilistic calculation methods. The deterministic solution methods are mainly divided into DC power flow method (LPF) [6], Benders algorithm [7], optimal power flow method (OPF) [8]-[9] and continuous power flow method (CPF) [10]-[11]. The probabilistic calculation method combines the theory of probability theory and mathematical statistics analysis with the method of ATC solution, which is computationally intensive [12].

In reference [2], the conventional uncertainty factors such as generator output, load fluctuation and component failure are considered in the establishment of the ATC model, but the new energy factor is not considered. Reference [3] uses a hierarchical clustering algorithm to divide the sample samples, and adds wind power based on comprehensive consideration of conventional uncertainties, but does not take into account the correlation between wind power. In the latest research, the reference [4] and [13] used Latin hypercube sampling (LHS) sampling combined with Cholesky decomposition and Copula theory to model the correlation of input random variables in ATC calculation, respectively, which is convincing, but a little complicated.

Based on this, this paper firstly studies and establishes the mathematical model of uncertainty factors from load, generator and line components, then considers the influence of uncertainty factors, takes the probability of network available transfer capability (PATC) as the objective function, and takes the probability of network available transmission capacity (PATC) greater than the given threshold as the flexibility constraint of the model, establishes a grid flexible planning model that considers the network probability available transmission capacity (PATC). Finally, obtain a grid planning scheme that meets the available transmission capacity level with a certain probability by genetic algorithm. The above method is used to expand the test system. The results of the example show that compared with other schemes, the model can minimize economic investment and increase the probability of available transmission capacity.

The structure of this paper is as follows. The second section introduces the uncertainty factor modeling method, the linear programming model for calculating the available transmission capacity (ATC), and the grid expansion planning model considering the probability available transmission capacity (PATC) and its solving algorithm. In the third section, the model system is validated by the model proposed in this paper. The fourth section is the conclusion of this paper.

2. The model formulation and its solving algorithm

2.1. Scenario generation method

The scenario generation in this paper considers the uncertainty of load, generator capacity and line fault. These three kinds of uncertainties cover three main basic components in the power network, which are highly representative.

1) Uncertainty model of loads

A probability model based on a normal distribution is used to represent the uncertainty of load growth. For the existing load node$i$, assuming that the original load is $P_{Di0}$, during the planning period, the change $\Delta P_{Di}$ of the load at that point is a random variable, obeying the normal distribution $\Delta P_{Di} \sim N(\mu, \sigma^2)$ where $\mu$ is the expected value, then the load at that point is $P_{Di} = P_{Di0} + \Delta P_{Di}$. 

2) Uncertainty model of generation capacities

The discrete probability distribution is used to describe the uncertainty of generator capacity. For the power node $i$ that may appear in the planning period, the probability of becoming a new power node is assumed to be $p$. For example, when the node $i$ is determined to be a new power node, the installed capacity of the point is expected to be $P_{Gik}$, and the probability of each possible installed capacity is $p_{ik}$. In this way, the distribution of discrete random variables is:

$$\Pr(X = P_{Gik}) = p_{ik}$$

In the formula, $0 < p_{ik} < 1$, $\sum_{k=1}^{M} p_{ik} = 1$, $k = 1, 2, \ldots, M$, $M$ is the possible installed capacity of each generating unit.

3) Uncertainty model of faults

The binomial distribution model is used to represent the uncertainty of line fault, in which 0 indicates that the line is in fault state and 1 indicates that the line is in normal operation state.

$$\Pr(X = k) = p^k (1 - p)^{1-k}$$

In the formula, $k = 0, 1$, $p$ is the forced outage rate of the line.

In the calculation, the corresponding load state, generator capacity state and line operation state are obtained by sampling according to the above three probability distributions.

2.2. Linear programming model for ATC calculation

Based on the DC power flow model, the linear programming model for calculating the available transmission capacity is as follows:

$$\max \text{ATC} = e^T d$$

s.t. $Sf + g = l + d$

$$f_{ij} - \gamma_{nj} n_{ij} (\theta_i - \theta_j) = 0$$

$$|f_{ij}| \leq n_{ij} f_{ij}$$

$$0 \leq g \leq \bar{g}$$

$$d \geq 0$$

Where $l, f, g, d, \theta, \bar{g}, e$ are the load column vector, the line current column vector, the power generation output column vector, the load growth column vector, the node phase angle column vector, the power generation output upper limit column vector, and the unit 1 column vector, $S$ is node branch association matrix, $n_{ij}, \gamma_{nj}, f_{ij}$ are the number of lines, admittance values, and line limits between lines $ij$. By solving this model, the available transmission capacity of the network can be obtained.

Taking into account the random uncertainties in the power system, the probabilistic available transfer capability (PATC) is defined as follows: Firstly, based on the random characteristics of the power system, the possible operation modes of the system are determined by simulating the random breaking and load changes of the power transmission equipment, and then the appropriate ATC is used to solve the ATC of the system under these operating modes. Finally, a comprehensive analysis of the ATC values in each operating state gives the expected value of the system ATC value. In this paper, the
Monte Carlo simulation method and the linear programming method are combined to calculate the value of PATC. In the calculation process, each uncertain factor uses the mathematical model described in A. For the deterministic state obtained by each sampling, a deterministic ATC calculation method based on the linear programming model is used.

2.3. Flexible grid planning model considering PATC

The grid planning model considering the probabilistic available transmission capacity of the network under uncertain information is as follows:

\[
\begin{align*}
\text{Min } v &= \sum_{(i, j) \in \Omega} c_{ij} n_{ij} \quad (9) \\
\text{Max } \text{PATC} &= E(e^T d) \quad (10) \\
Sf + g + r &= l + d \quad (11) \\
f_{ij} - \gamma_{ij} (n_{ij}^0 - n_{ij}) (\theta_i - \theta_j) &= 0 \quad (12) \\
|f_{ij}| &\leq (n_{ij}^0 + n_{ij}) k_{ij} f_{ij} \quad (13) \\
0 &\leq g \leq g_{\text{max}} \quad (14) \\
0 &\leq r \leq l + d \quad (15) \\
\Pr(e^T d \geq h) &\geq \beta \quad (16) \\
0 &\leq n_{ij} \leq n_{ij}^- , d \geq 0 \quad (17)
\end{align*}
\]

Where \(E, e, c_{ij}, n_{ij}^0, n_{ij}, \gamma_{ij}, f_{ij}\) are respectively the expected value operator, \(l\) vector, the investment cost of adding a single line between the branches \(i-j\), the number of original lines between the branches \(i-j\), and the number of lines increased between the branches \(i-j\), the maximum number of lines between the branches \(i-j\), the admittance of a single line between the branches \(i-j\), and the active transmission limit of a single line between the branches \(i-j\), \(I\) is the predicted load active column vector. \(g_{\text{max}}\) is the generator active output upper limit column vector, \(f, f_{ij}, g, r, \theta\) are the active power column vector of the branch considering the available transmission capacity of the network, the active power between the branches \(i-j\), the generator active output column vector, the minimum load shedding column vector, and the phase angle of the node \(i\), \(S\) is node branch association matrix, \(d\) is an active power column vector that can be increased by each load node when considering the network probability available transmission capability, \(h\) is the minimum threshold of the available transmission capacity of the system considering the available transmission capacity, \(\beta\) is the confidence that the network available transmission capacity is greater than the minimum threshold \(h\); \(\Omega, \Omega, \nu\) are the branch sets, load node sets and total investment costs of all lines that can be added.

Formula (9) and (10) are objective functions, which represent the minimum investment cost and the maximum available transmission capacity. In addition to the conventional power flow constraint, the constraint includes the probability constraint that the system PATC is greater than a given threshold (16) and the upper limit constraint of the number of available lines (17).
2.4. Solving algorithm

When solving the model (9)-(17), genetic algorithm is used to solve the model. Genetic algorithm is an adaptive heuristic global search algorithm based on the survival of the fittest rule and the mechanism of chromosome information exchange within the population in the process of biological evolution. It has been successfully applied in function optimization and other fields because of its simple, universal, robust, independent of problem model and suitable for parallel distributed processing. Genetic algorithm has been proved to have the ability to deal with nonconvex, nonlinear, mixed integer optimization problems [14], which is better than a series of mathematical methods in solving power grid expansion planning problems.

The general flow of using the genetic algorithm to solve the grid expansion planning model considering the probabilistic available transmission capacity is shown in Figure 1.

First, using the ATC linear programming model to obtain N initial planning schemes as the initial solution of the genetic algorithm, the investment cost minus the PATC minimum is recorded as $G$, then use the genetic algorithm to update the progeny solution and the investment cost minus the PATC minimum until the maximum genetic algebra is reached. Finally, the optimal solution is applied to a large number of scenarios. Finally, the optimal solution is applied to a large number of scenarios to verify whether the PATC of the scheme satisfies the chance constraint condition, and if so, the result is output, otherwise the calculation is recalculated.

![Figure 1. Flow chart for solving planning model considering PATC with genetic algorithm](image-url)
3. Case studies
According to the above model of power grid expansion planning based on chance constraints, matlab program is compiled and applied to the test system for expansion planning. The system is a six node test system [15], the grid structure diagram of the original system is shown in Figure 2, the basic parameters of the original system such as load, generator and line are shown in Table 1, Table 2 and Table 3, and the expansion planning data is shown in Table 4.

All simulations have been run using GUROBI 6.5 under MATLAB, on a computer with two Intel Xeon E5-2680 (2.4 GHz) processors and 128 GB of random access memory.

![Figure 2. Six-node test system](image)

**Table 1. Bus load data**

| Bus | 1 | 2 | 3 | 4 | 5 | 6 |
|-----|---|---|---|---|---|---|
| Load(MW) | 95 | 284 | 47 | 190 | 284 | 0 |

**Table 2. Generating unit data**

| Bus | Generating unit | Pmax(MW) | Pmin(MW) | Number of units |
|-----|-----------------|----------|----------|-----------------|
| 1   |                 | 30       | 0        | 2               |
| 1   |                 | 60       | 0        | 2               |
| 6   |                 | 120      | 0        | 1               |
| 6   |                 | 240      | 0        | 2               |
| 3   |                 | 60       | 0        | 2               |
| 3   |                 | 120      | 0        | 2               |

**Table 3. Branch data**

| Branch | From bus | To bus | Reactance(P.U./100 MVA Base) | Capacity (MW) |
|--------|----------|--------|------------------------------|---------------|
| 1      | 1        | 2      | 0.4                          | 100           |
| 2      | 1        | 4      | 0.6                          | 80            |
| 3      | 1        | 5      | 0.2                          | 100           |
| 4      | 2        | 3      | 0.2                          | 100           |
| 5      | 2        | 4      | 0.4                          | 100           |
| 6      | 2        | 6      | 0.3                          | 100           |
| 7      | 3        | 5      | 0.2                          | 100           |
| 8      | 4        | 6      | 0.3                          | 100           |
Table 4. Extended planning data

| Bus | Generating unit | | | |
|-----|-----------------|---------------|-----------------|---|
|     | | Pmax(MW) | Pmin(MW) | Number of units | Price(¥) |
| 1   | 180             | 0             | 1               | 8589200 |
| 3   | 180             | 0             | 1               | 8589200 |
| 5   | 180             | 0             | 1               | 8589200 |

| Branch | From bus | To bus | Reactance(P.U./100 MVA Base) | Capacity (MW) | Price(¥) |
|--------|----------|--------|-------------------------------|---------------|----------|
| 9      | 2        | 3      | 0.2                          | 200           | 872000   |
| 10     | 2        | 6      | 0.3                          | 200           | 872000   |
| 11     | 3        | 5      | 0.2                          | 200           | 872000   |
| 12     | 4        | 6      | 0.3                          | 200           | 872000   |

The above model is solved by the process described in the second section, and the planning scheme 1 is obtained, which is compared with schemes 2 and 3, 1 means new construction, 0 means no construction. Considering the uncertain factors, 100 scenarios are extracted, and the total cost of investment and PATC in each scenario is calculated. The results are shown in Table 5.

Table 5. Results

| Bus | Generating unit | Plan1 | Plan2 | Plan3 |
|-----|-----------------|-------|-------|-------|
|     | | Pmax(MW) | Pmin(MW) |     |     |
| 1   | 180             | 0     | 0     | 1    | 1    |
| 3   | 180             | 0     | 1     | 0    | 1    |
| 5   | 180             | 0     | 1     | 1    | 0    |

| Branch | From bus | To bus | | |
|--------|----------|--------|---------------|---|
| 9      | 2        | 3      | 1             | 1 |
| 10     | 2        | 6      | 1             | 1 |
| 11     | 3        | 5      | 1             | 1 |
| 12     | 4        | 6      | 1             | 1 |

| Investment cost(×10⁶) | 20.67 | 20.67 | 20.67 |
| PATC(MW)             | 600.26 | 528.71 | 0 |

It can be found that using the planning model proposed in this paper, a power grid planning scheme that satisfies the available transmission capacity level of a certain probability can be obtained, and the probabilistic transmission capability of the network can be improved under a certain economic level, so that the comprehensive benefit of the planning scheme is optimal. Under the same investment cost, scheme 1 has the highest probability of transmission in 100 random scenarios, while the new route of scheme 2 is the same as scheme 1, and the change of generator position leads to a slight decrease in the probability of available transmission capacity. Scheme 3 also only changes the position of the newly built generator, and this change makes the probability available transmission capacity greatly reduced or even zero. It can be seen that the location of the new generator has a greater impact on the probability of transmission capacity.

In summary, the planning scheme obtained by the method proposed in this paper takes into account the investment cost and probabilistic available transfer capability (PATC), which is comprehensive and optimal, effective, and can achieve good results.

4. Conclusions
In this paper, three representative uncertain factors in power grid planning are studied and the specific mathematical models describing each uncertain factor is established, then a large number of random scenarios are generated. In addition, a grid expansion planning model considering the probabilistic available transmission capacity under the influence of uncertainties is proposed. Finally, the genetic
algorithm is used to solve the model to obtain a power grid planning scheme that meets the transmission power level of a certain probability. The above method is used to expand the planning system. The results of the example show that compared with other schemes, the model can minimize economic investment under the condition of increasing the probabilistic available transmission capacity, and the overall benefit is better.

Acknowledgments
This work was supported in part by Key Technology Research and Application of Chongqing Power Grid Flexible Planning of Chongqing Electric Economic Research institute in 2019 (SGCQJY00GHJS1900074).

References
[1] Mu Yongzheng, Lu Zongxiang, Zhou Qinyong, et al. Optimized reliability balancing based transmission coordinating expansion planning for power grid with wind farms[J]. Power System Technology, 2015, 39(1): 16-22(in Chinese).
[2] Gao yajing. Research on available transfer capability considering uncertainties [D]. North China Electric Power University, 2007(in Chinese).
[3] Li Zhongcheng, Zhang Buhan, Duan Yao, et al. Fast calculation of probabilistic available transfer capability in power systems including large-scale wind farms[J]. Proceedings of the CSEE, 2014, 34(4): 505-513(in Chinese).
[4] Luo Gang, Chen Jinfu, Cai Defu. Probabilistic assessment of available transfer capability considering spatial correlation in wind power integrated system[J]. IET Gener Transm Distrib, 2013, 7(12): 1527-1535.
[5] North American Electricity Reliability Council. Transmission transfer capability: a reference document for calculating and reporting the electric power transfer capability of interconnected electric systems. USA, 1995.
[6] Landgren G L, terhune H L, Angel R K. Transmission interchange capability analysis by computer IEEE[J]. Trans on Power Apparatus and Systems, 1992, 91 (6): 748-754.
[7] Mohamed Shaaban, Liu H M, Li W X, et al. ATC calculation with static security constraints using Benders decomposition [J]. Proceedings of the CSEE, 2003, 23(8): 7-11.
[8] Pan X, Xu G Y. OPF based ATC calculation with static voltage stability constraints [J]. Proceedings of the CSEE, 2002, 22(11): 86-91.
[9] Wang F, Bai X M. Opf based transfer capability calculation [J]. Proceedings of the CSEE, 2002, 22 (11): 35-40.
[10] Breseti P, Lucarella D, Marannino P, et al. An OPF-based procedure for fast TTC analyses [C]. Power Engineering Society Summer Meeting, Chicago, 2002.
[11] Li G Q, Yao S W, Chen H H. Calculation of available transmission capability of AC / DC hybrid system based on interior point method [J]. Automation of Electric Power Systems, 2009, 33(3): 35-39.
[12] Zhou M, Ran R J, Li G Y. Assessment of available transmission capacity for wind power grid-connected systems [J]. Proceedings of the CSEE, 2010(22): 14-21.
[13] Wang Jun, Cai Xingguo, Ji Feng. A simulation method of correlated random variables based on copula [J]. Proceedings of the CSEE, 2013, 33(22): 75-82(in Chinese).
[14] Chung T S, Li Y Z, Wang Z Y. Optimal generation expansion planning via improved genetic algorithm approach [J]. International Journal of Electrical Power and Energy Systems, 2004, 26(8).
[15] Yousefi G, Sayyadi S, Latify M A. Mid-term Vulnerability Analysis of Power Systems under Intentional Attacks [J]. IET Generation, Transmission & Distribution, 2016.