Coordinated generation and transmission expansion planning approach based on chance-constraints using genetic algorithm

Ping Zhou¹, Peng Kang², Yuan Zhu¹, Ruiguo Chen¹

¹. State Grid Chongqing Electric Economic Research institute, Chongqing 400000, China;
². State Grid Chongqing, Chongqing 400000, China

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

Abstract. The grid planning is a crucial and basic work in the power system, but there are various uncertain factors in the power system, which cause dramatic influences to the size of the grid power investment, as well as the power system security and stability for next few years. Traditional planning methods are gradually hard to adapt the grid planning under situations especially with large amounts of uncertainties. To reduce the impact of uncertain factors of the power system, it is necessary to consider increasingly significant uncertainties in system planning. However, if all extreme scenarios all taken into account, generally, the optimization results will be really conservative. Therefore, to prevent a relatively conservative optimization scheme, this paper proposes a grid-based expansion planning model based on chance constraints which take fully considerations of system uncertain factors using genetic algorithm. Compared with other planning schemes, this method comprehensively considers the investment cost and the level of load loss. Finally, a test system with six nodes is used to verify the effectiveness of the proposed method. The economics of the optimization scheme using the proposed approaches are observed using the test system.

1. Introduction
With the advancement of power market reforms, due to uncertainties such as future national policies, environmental changes, energy demand, and cyclical fluctuations in global economic development, the development of power grid planning schemes is beginning to face more and more complex uncertainties. First of all, the traditional management mode of transmission, transmission and distribution has been broken. The site of the new power plant and its installed capacity have been decided by the power generation company. The grid planning workers cannot fully consider the impact of the power planning results in the power grid planning process, which makes the power supply become a major uncertainty in the power grid planning process. Secondly, with the continuous expansion of the breadth and depth of China's opening-up, the fluctuation of global economic development has more and more impact on China's economy [1]. The adaptability of the planned power grid based on the economy to this unpredictable load fluctuation obviously needs to be greatly reduced, therefore, the future load data is another unpredictable uncertainty factor in the process of power grid planning. Finally, an important factor affecting the reliability of power grid is line fault, which is also a kind of uncertainty factor.
In the method of dealing with uncertain factors [2]-[4], the paper [5] introduces the uncertainty of load and power supply into the mathematical model of transmission network planning, and obtains a more economic planning scheme which can adapt to the uncertainty of load and power supply at the same time. In reference [6], the uncertainty of load is treated by interval mathematics, and the load measurement value with error in interval number simulation is obtained, and the influence of the measurement error on the voltage value of power flow calculation is analyzed. In reference [7], the blind number BM model and its characteristics are introduced. The blind number is used to describe all kinds of uncertain information in power grid planning. A power grid planning model based on the blind number BM model is proposed, and a flexible power grid planning scheme with the best economy and reliability is obtained by using the cost-benefit analysis method. Based on the uncertainty of power supply and load, and taking into account the influence of environmental constraints, references [8]-[9] describe the adaptability of power grid planning scheme from multiple perspectives. In [11]-[11], from the aspects of stochastic theory, fuzzy set theory and credibility theory, the research results of domestic and foreign uncertain factor modeling methods and the research results of transmission network planning methods based on uncertainty theory are reviewed. Based on this, this paper studies and establishes the specific mathematical model of the uncertain factors, including the uncertain factors from the load, generator and line components, and models them. Considering the influence of the uncertain factors, the chance constraint planning theory is introduced into the flexible planning of power grid, and the flexible expansion planning model of power grid based on the chance constraint planning is established. 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 satisfying the load demand as much as possible. The structure of this paper is as follows. The second section introduces the grid expansion planning model and solving algorithm based on the chance constraint. The third section uses the model proposed in this paper to verify the example system. 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 \(\Delta P_{Di} \sim N(\mu_i, \sigma_i^2)\) where \(\mu_i\) 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:

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

(1)
In the formula, 0 < p_{ikp} < 1, \sum_{k=1}^{M} p_{ikp} = 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} \quad (2)

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. Planning model

In this paper, the objective is to minimize the investment cost of the transmission line, which allows the generated planning scheme to fail to meet the line overload constraint under some extreme ground conditions, but the probability of this situation must be less than a certain level of confidence. On this premise, a flexible planning mathematical model of power grid based on chance constraint planning is constructed.

Min invest = \sum_{i,j \in \Omega} c_{ij} n_{ij} \quad (3)

The objective function is to minimize the investment cost, where \( c_{ij} \) and \( n_{ij}^0 \) are the investment cost of adding a single line between branches \( i-j \) and the number of original lines between branches \( i-j \).

\[ Sf + g = l \quad (4) \]

Equation (4) is constrained by Kirchhoff's first law, \( S \) is the node branch correlation matrix, \( f \) is the branch active power train vector, \( g \) is the generator active power train vector, \( l \) is the predicted load active random train vector.

\[ f_{ij} - \gamma_{ij} (n_{ij}^0 + n_{ij}) (\theta_i - \theta_j) = 0 \quad (5) \]

Equation (5) is constrained by Kirchhoff's second law, \( f_{ij} \) is the active power between branches \( i-j \), \( \gamma_{ij} \) is the mobility of a single line between branches \( i-j \), \( n_{ij}^0 \) is the number of original lines between branches \( i-j \), \( n_{ij} \) is the number of lines actually added between branches \( i-j \), and \( \theta_i \) is the phase angle of node voltage.

\[ \Pr( |f_{ij}| \leq (n_{ij}^0 + n_{ij}) k_{ij} f_{ij} ) \geq \alpha \quad (6) \]

Equation (6) is the limit crossing probability constraint of line power flow, which is based on the form of chance constraint, \( \alpha \) is the set limit crossing probability value of line, \( f_{ij} \) is the upper limit of active power transmission of a single line between branches \( i-j \), and \( k_{ij} \) is the active transmission load rate of a single line between branches \( i-j \).

\[ 0 \leq g_i \leq \bar{g} \quad (7) \]

Equation (7) is the upper limit constraint of generator output, and \( \bar{g} \) is the upper limit vector of generator active output.

\[ 0 \leq r_i \leq l \quad (8) \]

Equation (8) is the node load shedding constraint, and \( r_i \) is the minimum load shedding column vector.
Equation (9) is the N-1 constraint of line fault, where \( t = 1, 2, \ldots, m \) represents the mode of \( m \) lines being disconnected respectively, and \( v = 1, 2, \ldots, m \) represents the running line. Inequality constraint \( S_v^{(t)} < S_v^{\text{max}} \) indicates that the apparent power of the line is less than its allowable transmission power \( S_v^{\text{max}} \) when line \( t \) is disconnected. This constraint indicates that when any line fails, there is no line out of limit or load shedding in the system.

\[
0 \leq n_{ij} \leq \overline{n}_{ij} \tag{10}
\]

Equation (10) is the upper limit of the number of circuits of the transmission corridor, and \( \overline{n}_{ij} \) is the maximum number of lines that can be added between the branches \( i-j \).

2.3. Solving algorithm

When solving the model equation reference goes here(3)-(10), 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 [11], which is better than a series of mathematical methods in solving power grid expansion planning problems.

The general process of using genetic algorithm to solve the flexible power grid planning model based on chance constrained planning is shown in Figure 1. First of all, an initial planning schemes are obtained by using the minimum load shedding model as the initial solution of genetic algorithm. The optimal investment cost is recorded as \( g \). the genetic algorithm is used to update the offspring solution and the optimal investment cost until the maximum genetic algebra is reached. The optimal solution is applied to a large number of scenarios to check whether it meets the chance constraints. If so, the result is output, otherwise the calculation is carried out again.

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 [12], 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.
Initialize \( i = 0, j = 0 \)
Set the initial solution number \( N \) and the maximum genetic algebra \( M \)

Generate \( k \) scenarios and use the minimum load shedding model to get the economic optimal solution \( n_i = 1 \)

\( i < N ? \)

\( N \) initial solutions \( n \) are obtained, where the optimal investment cost is recorded as \( G \)

The genetic algorithm is used to calculate the progeny solution \( n \), the optimal investment cost of the child \( g_j = 1 \)

\( j < M ? \)

\( n = n' \)

\( g < G ? \)

Apply the final generation investment optimal solution to a large number of scenarios

Meet chance constraints \( Y \)

Output result

**Figure 1.** Flow chart of solving chance constrained power grid planning model with genetic algorithm

**Figure 2.** Six-node test system

**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               |
| 3   |                 | 60       | 0        | 2               |
| 6   |                 | 240      | 0        | 2               |
| 3   |                 | 60       | 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            |

Table 4. Extended planning data

| Bus | Generating unit | Pmax(MW) | Pmin(MW) | Number of units | Price(¥) |
|-----|-----------------|----------|----------|-----------------|----------|
| 1   |                 | 120      | 0        | 1               | 4360000  |
| 3   |                 | 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 genetic algorithm process described in Section II is used to solve the problem and obtained that plan 1, 1 represents new construction and 0 represents no construction. Compared with plan 2 and plan 3, 100 scenarios are selected considering uncertainty factors. The total loss of load and total investment cost of each scenario are calculated. The results are shown in Table 5.

Table 5. Results

| Bus | Generating unit | Plan1 | Plan2 | Plan3 |
|-----|-----------------|-------|-------|-------|
| 1   |                 | 1     | 1     | 1     |
| 3   |                 | 0     | 1     | 0     |
| 5   |                 | 0     | 1     | 0     |

| Branch | From bus | To bus | Plan1 | Plan2 | Plan3 |
|--------|----------|--------|-------|-------|-------|
| 9      | 2        | 3      | 0     | 0     | 1     |
| 10     | 2        | 6      | 1     | 1     | 0     |
| 11     | 3        | 5      | 0     | 0     | 1     |
| 12     | 4        | 6      | 1     | 1     | 0     |

Investment | 14.69 | 14.69 | 14.69 |
It can be found that the scheme obtained by using the chance constrained power grid expansion planning model allows load shedding in some extreme cases, so that the comprehensive benefit of the planning scheme is optimal. Under the same investment cost, the total load loss of scheme 1 is the smallest in 100 random scenarios. In scheme 2, the new line is the same as scheme 1, and the change of generator position leads to a great increase of load loss level. In scheme 3, the new generator position is the same as scheme 1, while the change of new line causes a slight increase of load loss level, but it is better than scheme 2.

To sum up, the planning scheme obtained by the method proposed in this paper considers both the investment cost and the level of loss of load, which is comprehensive optimal, effective and can achieve good results.

4. Conclusions

Aiming at the three typical uncertain factors in power grid planning, this paper studies and establishes a specific mathematical model to describe the uncertain factors, generates a large number of random scenes, considers the influence of uncertain factors, and establishes a flexible expansion planning model of power grid by using the chance constrained programming theory. The above method is used to expand the planning of the example system. The result of the example shows that compared with other schemes, the model proposed in this paper allows load shedding in extreme cases, and can minimize the economic investment and achieve the optimal comprehensive benefit of the planning scheme under the condition of satisfying the load demand as much as possible.

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] Huifang Zhang. The role of load forecasting management in the new economic situation [J].Co-Operative Economy & Science, 2015(12):107.
[2] Haibao Zhai. Models and algorithms of electric power network flexible planning under multi uncertainty [D]. Doctoral Dissertation of Shanghai Jiaotong University, 2007.
[3] Yan Zhang, Zhangchao Chen. An approach for transmission system planning incorporating uncertainties [J]. Power System Technology, 1999, 23(3): 15-18.
[4] Haibao Zhai, Haozhong Chen, Chunlin Chen, et al. The Minimal Expectant Regret Concerned Electric Power Network Planning under Flexible Constraints [J]. Journal of Shanghai Jiaotong University, 2005, 39(Sup.1):27-30.
[5] Escobar A H, Romero R A, Gallego R A. Transmission network expansion planning considering uncertainty in generation and demand[C]. Transmission and Distribution Conference and Exposition: Latin America, 2008 IEEE/PES, 2008.1-6
[6] Wang Zian, Alvarado F L. Interval arithmetic in power flow analysis[J]. IEEE Trans. on Power Systems, 1992, 7(3): 1341-1349.
[7] Haozhong Chen, Haifeng Zhu, Jianmin Wang. Electric Power Networks Flexible Planning via the Blind Model (BM) of Unascertained Number [J]. Journal of Shanghai Jiaotong University, 2003(9): 7-12.
[8] EI-Sheikhi, Farag Ali, Billinton, Roy. Load forecast uncertainty considerations in generating unit preventive maintenance scheduling for single system[C]. IEE Conference Publication, 1991, n 338: 241-245.
[9] Bresesti P, Capasso A, Falvo M C, et al. Power system planning under uncertainty conditions. criteria for transmission network flexibility evaluation[C]. Power Tech Conference Proceedings, 2003 IEEE Bologna , 2003:2-6.

[10] Alvarez J, Ponnambalam K, Quintana V H. Transmission Expansion under Risk using Stochastic Programming[C]. International Conference on Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. 2006:1-7.

[11] Libo Zhang, Haozhong Chen, Pingliang Zeng, Qinyong Zhou, Lu Liu. Transmission Network Planning Approaches Based on Uncertainty Theories [J]. Automation of Electric Power Systems, 2016,40(16):159-167.

[12] T.S. Chung, Y.Z. Li, Z.Y. Wang. Optimal generation expansion planning via improved genetic algorithm approach[J]. International Journal of Electrical Power and Energy Systems, 2004,26(8).

[13] Yousefi G , S. Sayyadi S , Latify M A. Mid-term Vulnerability Analysis of Power Systems under Intentional Attacks[J]. IET Generation, Transmission & Distribution, 2016.