Flexibility planning of transmission grid based on correlation of generation and transmission

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Abstract. The sharp development of power generation technology involving the clean energy boosts the grid-connected proportion of clean power such as wind and light, whereas the randomness and volatility of their outputs contribute to the strong uncertainty of multi-space-time coupling in the power system, seriously affecting the security and stability of the power grid. Hence, the traditional grid planning has been unable to meet the needs of high proportion of grid-connected clean energy. However, the flexibility of the power system can effectively reflect the system's ability to withstand the impact of uncertainty and is of great significance to the integration of the high proportion of clean energy. Based on the original definition of flexibility, this paper proposes a flexibility index system considering supply and demand balance, grid layout and power flow distribution, and comprehensively evaluates the power system's acceptance of clean energy. Besides, a two-level extended programming model of transmission network with flexibility index system is established. The improved chaotic crossover genetic algorithm is used to solve the planning model. The feasibility and practicability of the proposed index system and planning model are verified by the simulation of the Garver-18 node system respectively.

1. Introduction

In recent years, along with the depletion of traditional fossil fuels and the deterioration of global environmental problems, the technology of renewable energy for power generation is developing rapidly. To gradually get rid of the dependence on fossil fuels, it is imperative to develop the carbon-free energy and promote the diversification of energy consumption patterns. China has proposed that the proportion of renewable energy be increased to 60% by 2050 [1]. However, the strong uncertainty of multiple space-time coupling brought by the large-scale and grid-connected clean energy will seriously threaten the operation of the power system. The flexibility of power system can effectively measure the system's ability to withstand the impact of uncertainties on multiple time scales, which is of great significance to the integration of high proportion of clean energy into the grid, thus becoming the research focus [2].

At present, the research on flexibility of power system both at home and abroad is still in its infancy where attentions are mainly attached to the basic concept and quantitative evaluation of flexibility. O’Malley M [3-5] and other scholars initially defined the concept and directionality of flexibility, proposing a set of quantitative indicators.

In terms of transmission network planning, the transmission network planning that aims at economy and reliability under the traditional operation mode tends to be completed. While for the
planning including the renewable energy, there also exists some research fundamentals. However, under the background of large-scale grid-connected renewable energy, many problems in transmission network planning such as uncertainties of influences, complicated constraints and diversification of decision-making indicators are becoming increasingly serious. Due to the lack of unified and effective indicators to judge the planning results, the current research on transmission grid planning is faced with new challenges [6].

In view of the existence of above problems, this paper expands the definition of flexibility as the generalized flexibility of the entire power system to the indefinable endurance and describes the new definition through the supply and demand balance of electricity consumption, the rational arrangement of grid structure and the uniform distribution of power flow on multi-time scale. Meanwhile, an index system of flexibility including the flexibility of supply and demand balance, network structure and operation is proposed. Based on this index system, considering the economy, safety and reliability, a two-level expansion programming model of transmission network is established. Finally, by means of chaos crossover genetic algorithm, the Garver-18 node system is respectively used to solve the planning model, proving the feasibility and practicability of the proposed index system and planning model.

2. Flexibility of supply and demand balance
The flexibility indicators of power system supply and demand balance are built on the direction and time scale characteristics, power balance at different time scales and demand and supply of electricity, which describe the flexibility of power system from the aspect of power balance.

2.1. Flexibility requirements of power system
At different timescales, the uncontrollable fluctuation of power in the power system can be divided into the flexibility requirements of the power supply side and the load side.

2.1.1. Flexibility requirements of power supply side
The demand for flexibility on the power side mainly comes from the output fluctuation of renewable energy. According to the characteristic of the output of renewable energy unit, it can be divided into two parts, one part is the forecast value and the other is the forecast error value, which is expressed as equation (1)

\[ P_{CPG}(t) = P_{CPG,F}(t) + P_{CPG,E}(t) \]  

Where: \( P_{CPG}(t) \) is the output value of renewable energy at time \( t \), \( P_{CPG,F}(t) \) is the forecast value and \( P_{CPG,E}(t) \) is the forecast error value. The flexibility needs of power-side only come from the forecast error of renewable energy output. Since the output forecast for renewable energy is rolling forecast, the average of forecast percentage error \( E_{MAPE} \), which is related to the forecast method and sample interval \( \tau \), is used to replace \( P_{CPG,E,AVE}(t) \) as the equation (2).

\[ P_{CPG,E,AVE}(t) = \pm E_{MAPE} \cdot P_{CPG,F}(t) \]  

\[ F_{up}^{N}(t,\tau) = P_{CPG,E}(t), P_{CPG,E}(t) < 0 \]  

\[ F_{down}^{N}(t,\tau) = P_{CPG,E}(t), P_{CPG,E}(t) > 0 \]  

Where: \( \tau \) is for the sample interval, the same as forecast length. \( F_{up}^{N}(t,\tau) \) and \( F_{down}^{N}(t,\tau) \) are the flexibility needs of the upside and down respectively from time \( t \) to \( t + \tau \).
2.1.2. Flexibility requirements of load side  The demand for flexibility of load side mainly derives from system failure load. The system’s load shedding is related to its operating status. When the power system suffers the loss load due to failure, the down flexibility is required.

\[ P_{LF}(t) = P_{LOAD}(t) \cdot LOLP \]  

\[ F^N_{down}(t, \tau) = P_{LF}(t) \]  

Where: \( F^N_{down}(t, \tau) \) is the down flexibility demand; \( P_L(t) \) is the system load; \( P_{LOAD}(t) \) is the total load of the system; \( P_{LF}(t) \) is the loss load from the failure at time \( t \); \( LOLP \) is the probability of loss load, the value of which is associated with the current operate state of the system.

2.2. Power system flexibility resources  
As the basis of the assurance for flexible operation of power system, flexible resources can meet the flexible demand generated on the corresponding time scales or longer, and improve the ability of power system to deal with the power fluctuation of uncertainties. At present, the adjustable units are most widely-used flexibility resources.  
Adjustable units, including thermal power, hydropower and other generating units of short response time, can provide the upside and down flexibility within the scope of its output according to its operating conditions.

\[ \left\{ \begin{array}{l} F^S_{up}(t, \tau) = \min \left[ R_{up} \cdot \tau, P_{g_{max}} - P_g(t) \right] \\ F^S_{down}(t, \tau) = \min \left[ R_{down} \cdot \tau, P_g(t) - P_{g_{min}} \right] \end{array} \right. \]  

Where: \( R_{up} \) and \( R_{down} \) are the up and down power ramping capability in adjustable unit time period, \( P_{g_{max}} \) and \( P_{g_{min}} \) are the upper and lower limits of adjustable unit output, \( P_g(t) \) is the unit current output power, \( S \) is the supply, \( F^S_{up}(t, \tau) \) and \( F^S_{down}(t, \tau) \) are the up and down flexibility supply.

As a kind of flexible resources, the energy storage device provides flexibility for system on the basis of its charge status, charge-discharge capability and charge-discharge strategy. The power system can also provide flexibility for itself by cutting off some of the renewable energy output or load.

2.3. The supply and demand balance of flexibility and its index  
2.3.1. The supply and demand balance of flexibility. Based on the above description of resource and requirements for flexibility, the flexibility of supply and demand balance of power system is defined, which only considers the uncontrollable power fluctuations under the safe operation of system, regardless of the fixed unit and load in the system.

\[ F_D(t, \tau) = \sum_{t \leq \tau} F^S_{up}(t, \tau_j) - F^S_{down}(t, \tau_j), D = \{up, down\} \]  

Depending on the time scale characteristics of flexibility, time-scale flexible resources can respond to a fairly or long-term flexibility requirement on a time scale.

2.3.2. The index of flexibility for supply and demand balance. Owing to the frequent occurrence of large shortage of flexibility resource at a short time, the mere measurement of the insufficient expectations of flexibility within a period of time cannot characterize the relationship of the lack of flexibility with its emergence duration, thus proving to be little importance. in view of the above phenomenon, the definition of between supply -demand balance flexibility Indicators are as follows
Insufficient degree of flexibility \( L_{DF}^D \) (MW/min):

\[
L_{DF}^D = \sum_{F_{i}(t, \tau_{i})>0} \frac{F_{i}(t, \tau_{i})}{T_{DL}}, D = \{up\, \text{or} \, down\}
\]  

(8)

Insufficient rate of flexibility \( E_{LF}^D \):

\[
E_{LF}^D = \frac{T_{DL}}{T}, D = \{up\, \text{or} \, down\}
\]  

(9)

Where: \( T_{DL} \) is the total time of lack of flexibility during operation, \( T \) is the total time during.

The insufficient degree and probability of flexibility, rose from the supply-demand balance and based on the balance of source and load, describe the ability of the system to deal with the fluctuation of power uncertainty from the perspective of the insufficient flexibility resources.

3. The power grid bi-level programming model

Based on the flexibility index of power system, this paper synthetically measures the ability of power system to deal with uncertain impact from three aspects of power balance, grid structure and power flow distribution. With the new line and flexible unit are taken as variables, the grid and source coordinated planning is conducted. Under the premise of meeting the demand of loop number of new lines, the number of new units and safe operation of power grid, a bi-level programming model of multi-objective optimization established with the planning economic cost, flexibility index, constraint punishment of violation for the grid security included.

3.1. The upper level planning model

The variables with subscripts '-'can be returned by the lower-level planning.

\[
F = \min (f_1, f_2)
\]  

(10)

The objective functions are as follows:

\[
f_1(C_{total}) = C_{total}
\]  

(11)

\[
C_{total} = C_F + C_{build,l} + C_{build,m}
\]  

(12)

\[
C_F = \sum_{i \in \Omega} \lambda_i W_{F,i}
\]

\[
C_{build,l} = (k_1 + k_2) \sum_{i \in \Omega} c x_i k_2 Z_i
\]

\[
C_{build,m} = \sum_{i \in \Omega} c \rho_i C_i Z_i
\]  

(13)

\[
k_i = r(1+r)^n / [(1+r)^n - 1]
\]  

(14)

Where: \( C_F \) is the flexible resource calling fee, \( C_{build,l} \) is the line construction fee, \( C_{build,m} \) is the flexible unit construction fee, \( \lambda_i \) is the calling cost for flexible resource units, \( W_{F,i} \) is the flexibility resource call total, \( \Omega \) is the flexibility resource collection, \( k_1 \) is the capital recovery factor, \( r \) is the discount rate, \( n \) is the engineering economic applicability, \( k_2 \) is the project fixed operating rate, \( c \) is
the line unit construction cost, \( x_y \) and \( l_y \) are the line construction circuit number and line length, \( Z_y \) and \( Z \) are the decision variables, \( \Omega_2 \) is the collection of lines to be built, \( C_{pi} \) is the unit capacity construction cost of unit to be built, \( G_i \) is the unit capacity to be built, \( \Omega_3 \) is the collection of units to be built.

\[
f_2(O) = \sum_{i \in \Omega_4} P_{eni} H_i
\]

Where: \( P_{eni} \) is the penalty coefficient for violating grid safety, \( H_i \) is the violation of grid security violations, \( \Omega_4 \) is the collection of violations of safe operation of the grid.

The upper planning model constraints are as follows:

\[
s.t. \quad -B_0 + P_G + P_F + P_{CPG} = P_L
\]

\[
x_{ij,\min} \leq x_{ij} \leq x_{ij,\max}, i,j \in N, x_{ij} \in Z
\]

\[
\begin{align*}
|P_{G,i}| &\leq (x^{N-1}_y + x^{N-1}_y) P_{max,ij} / \in N_i \\
P_{G,i,\min} &\leq P_{G,i} \leq P_{G,i,\max}, i \in N_G
\end{align*}
\]

\[
\begin{align*}
|P_{G,i}^{N-1}| &\leq P_{G,i,\max} / \in N_i^{N-1} \\
P_{G,i,\min} &\leq P_{G,i}^{N-1} \leq P_{G,i,\max}, i \in N_G^{N-1}
\end{align*}
\]

Where: \( B, \theta, P_G, P_F, P_{CPG} \) and \( P_L \) are system node admittance matrix, node voltage phase angle vector, system node conventional generator output vector, flexibility resource output vector, renewable energy output vector and load power vector, \( x_y \) is the number of new lines, \( x_{ij,\min} \) and \( x_{ij,\max} \) are the minimum and maximum number of lines to be built, \( N_i \) is the collection of system lines under normal operating conditions, \( P_{G,i,\min} \) and \( P_{G,i,\max} \) are the minimum and maximum output of the unit, \( P_{G,i} \) is the unit output, \( N_G \) is the collection of system units under normal operating conditions, \( x_y^0 \) is the number of existing lines, \( P_y \) and \( P_y^{max} \) are the actual power and maximum capacity per line, \( N-1 \) means the \( N-1 \) operating status.

3.2. The lower level planning model

In this model, the variable is the new-constructed flexibility units and the target function is the minimum of the total usage of flexibility resources, the insufficient degree and rate of flexibility.

\[
V = \min(v_1, v_2, v_3)
\]

The objective functions are as follows:

\[
v_1(W_F) = \sum_{i \in \Omega_1} W_{F,i}
\]

\[
v_2(L^{up}_{LF}) = L^{up}_{LF}, D = \{up, down\}
\]
The lower planning model constraints are as follows, the variables with subscripts ‘-’ can be returned by the upper-level planning:

\[ S = \sum_{g} P_{g,i} - \left( -B_{0}^{+} + P_{F}^{+} + P_{PG}^{-} \right) = P_{L}^{+}, s \in N_{S} \]  

\[ P_{g,i\min} \leq P_{g,i} \leq P_{g,i\max}, i \in N_{g} \]  

Where: ‘S’ means the typical operating scenario, \( P_{g,i} \) is the actual output of the unit, \( P_{g,i\min} \) and \( P_{g,i\max} \) are the upper and lower limits of unit output.

4. Example simulation

In order to verify the effectiveness of proposed flexibility index and bi-level programming model, the modified Garver-18 node is respectively used to solve the planning model above. And the improved genetic crossover genetic algorithm is adopted to conduct the optimization. Meanwhile, the improved non-linear principal component analysis is applied to assess and calculate the fitness of multi-objective function for the upper and lower layers, which guarantees the objectivity and reasonableness of the evaluation results.

This paper uses Garver-18 node system as an example to carry out simulation calculation. According to the simulation calculation, the network planning is shown in Figure 1. The planning results are shown in Table 1, where the dotted line represents the new line.

**Figure 1.** Network planning of Garver-18 node system.

**Table 1.** Planning results of Garver-18 node system.

| Parameter                              | Result                                |
|----------------------------------------|---------------------------------------|
| Expansion line and its quantity        | 1-11(1), 2-3(1), 4-7(1), 4-16(2), 5-11(1), 5-12(2), 6-13(1), 6-14(1), 7-9(1), 7-13(1), 7-15(1), 9-16(2), 10-18(2), 11-12(1), 11-13(1), 12-13(1), 14-15(2), 16-17(1), 17-18(1) |
| Construction cost (USD)                | 60,548,212.763                        |
| Normal penalty fee (USD)               | 0                                     |
| N-1 penalty fee (USD)                  | 0                                     |
| \( E_{LF}^{up} \) (MW / min)           | 2.201                                 |
| \( E_{LF}^{down} \) (MW / min)         | 1.976                                 |
| \( E_{LF}^{up} \)                       | 0.254                                 |
| \( E_{LF}^{down} \)                     | 0.178                                 |
In order to verify the superiority of the plan, this paper compares it with the existing economic plan [7]. Although the planning model used in this project is slightly more expensive, it can adapt to the access of a high proportion of clean energy. When clean energy is connected to the grid, the traditional planning scheme with economic planning as the target has been overloaded in the case of N-1 operation, and it has been unable to meet the safe and reliable operation of the system. The annual electricity shortage expectation of this paper is 96.78% lower than that of the economic plan. As shown in table 2.

| Program               | Construction cost (USD) | N-1 penalty fee (USD) | Annual electricity shortage expectation (MW·h) |
|-----------------------|-------------------------|-----------------------|------------------------------------------|
| This paper            | 60,548,212.76           | 0                     | 12538.9                                  |
| Related literature    | 52,530,419.83           | 1,680,602.7           | 389332.64                                |

In summary, the comparison results show that the flexibility index proposed in this paper can effectively improve the capacity of power system to absorb renewable energy.

5. Conclusions

Under the background of a high proportion of renewable energy into the power grid, this paper proposes a flexibility evaluation index system for power system based on the problem of power balance, network structure and operation state brought by renewable energy connected into the grid. Meanwhile, a two-level expansion planning model of transmission network is established and the improved chaotic crossover mutation genetic algorithm is adopted to solve the optimal planning scheme. Compared with the traditional and actual grid planning scheme, the proposed scheme can not only satisfy the demand of the higher proportion of grid-connected renewable energy, and effectively improve the capacity of absorbing the renewable energy, but also improve the ability of the power system to withstand the impact of uncertainties from the perspective of optimizing grid structure and power flow distribution, so as to verify the feasibility and practicability of the planning. Finally, the simulation results are in line with the actual needs of the project.

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