A Joint Grid-Source Planning Method Considering Adaptability of Power System

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Abstract. With the large-scale renewable energy access to the power grid, the construction and operation status of the power system have been greatly changed. Therefore, the adaptability of power system to deal with the fluctuation and uncertainty of renewable energy is of great significance to ensure the safe and stable operation of the system and promote the consumption of renewable energy. Based on the structural characteristics and operation status of the power system with high proportion of renewable energy, the adaptability index of the system construction and generators capacity is proposed, which takes into account the security, validity, stability and supply-demand balance of the power system, and comprehensively evaluates the acceptance capacity of the system to the renewable energy. On this basis, a multi-objective power system planning model based on grid-source coordination considering both economy and adaptability is established. The optimal scheme is obtained through the comprehensive decision of the optimal scheme set by the nonlinear improved principal component analysis. Finally, the effectiveness of the adaptability index and the planning model is verified by an example simulation with the improved Gaver-18 system.

Keywords: Transmission grid planning; Adaptability; Grid-source coordination; High-penetration renewable energy.

1. Introduction

With high volatility and high uncertainty, the introduction of a large number of renewable energy sources will affect the operation mode of power grid and so on. There is an urgent need to build a power system with high adaptability to follow the trend towards large-scale integration of renewable energy sources. In the literature [1-3], disparate planning grid models have been established to make the planning scheme suitable for various uncertain scenarios. Further considering the matching of power sources with the power grid, the abandoned renewable energy is reduced through coordinated planning in the literature [4-7]. However, the above studies focus on the planning model itself as well as the description of uncertainty, adaptability of renewable energy to the grid is measured by the abandoned energy. And the assessment is so simple that the influence of the renewable energy connected with grid cannot be fully showed.

Traditional researches about system of power adaptability mainly focus on the security adaptability assessment. Based on the homogeneity theory and the complex-network theory, the entropy index system with weighting factor is established to reflect the self-organized criticality of the power system in the literature [8]. The principle of flexible equilibrium is described in the literature [9]. Meanwhile, the methods to enhance flexibility of power system is also mentioned. The theory of flexibility lacks
sufficient consideration of the operating state. Therefore, in order to cope with a large number of high proportion of renewable energy connected to grid, the flexibility index system needs to be improved. This paper proposes an index system of adaptability suits for system which renewable energy ratio is high in order to evaluate the adaptability of grid-construction and generator capacity to the grid-connected renewable energy. The index of grid-construction covers all operating states and the index of generator capacity reflects the adequacy of system regulation ability to deal with the fluctuation of renewable energy output and forecast error from the coordination of supply and demand. A multi-objected grid-source coordinated planning model is presented with considering the construction cost and operation constraints based on the adaptability index. The method of PCA is used to get the optimal planning scheme. Lastly, simulation of modified Gaver-18 system is taken out to demonstrates effectiveness of the planning model and adaptability index.

2. The Grid-construction Adaptability and Grid-construction Adaptability Index

2.1. The Grid-construction Adaptability

The grid-construction adaptability is defined as the ability of grid to maintain security, validity and stability depending on its own construction when uncertain disturbances occur. The evaluation of grid-construction adaptability is presented from the following aspects:

1) Security adaptability (SA). It reflects the power-flow uniformity. The more uniform the load at each line is, the stronger the ability of the grid-construction to withstand uncertain disturbances is under the same load\(^{[10]}\).

2) Validity adaptability (AA). It reflects the maximization of utilization of the grid of power. Overbuilding of the grid can be avoided by keeping the average operating validity of each line high.

3) Volatility adaptability (OA). It reflects high power-flow inertance. For random disturbance, the smaller the power volatility of each line is, the more stable the operation of system is.

2.2. The Grid-construction Adaptability Index

The power flow will be varied due to the fluctuation of renewable energy power, so the system operation state is in change all the time. Therefore, the desired line load rate \( \lambda \) and the volatility of line power \( V \) reflect the operating status of each transmission line. The desired line load rate \( \lambda \) is proposed to reflect the desired value of actual line load rate. It refers each line average load level under a certain scene.

\[
\lambda_i = \frac{E(P_{i,\text{des}})}{S_{i,\text{max}}}
\]  

Where \( \lambda_i \) is the desired line load rate of line \( i \), \( P_{i,\text{des}} \) is the practical transferring power of line \( i \), \( E(P_{i,\text{des}}) \) is the desired value of \( P_{i,\text{des}} \), \( S_{i,\text{max}} \) is line \( i \) transferring capacity. Here, \( P \) refers to full power instead of active power.

The volatility of line power \( V_i \) is defined as the rate of the practical power volatility and the power volatility capacity of a line.

\[
V_i = \left( E(P_{i,\text{des}}^2) - E(P_{i,\text{des}})^2 \right)^{1/2} / \min \{ |S_{i,\text{max}} - E(P_{i,\text{des}})|, |E(P_{i,\text{des}})| \}
\]  

Where \( V_i \) is the line power volatility of line \( i \), \( E(P_{i,\text{des}}^2) \) is the desired value of \( P_{i,\text{des}} \), \( E(P_{i,\text{des}}) \) is the actual transferring power fluctuation of line \( i \), \( \min \{ |S_{i,\text{max}} - E(P_{i,\text{des}})|, |E(P_{i,\text{des}})| \} \) is transferring power volatility capacity of line \( i \).

From the overall grid, the grid-construction adaptability index is proposed as follows based on \( \lambda \) and \( V \) consequently.

1) Security adaptability index \( f_{\lambda\delta} \). It reflects the standard deviation of the desired load ratio of the whole lines. The smaller the index is, the more balanced the load level of each line is, and the safer the power grid is\(^{[11]}\).
Where $N$ is number of lines, $\lambda_{\text{ave}}$ is the average of desired load rate of all lines.

2) Validity adaptability index $f_{AA}$. It reflects the weighted average of the desired load ratio of all lines. The larger the index is, the more efficient the grid of power is.

$$f_{AA} = \sum_{i=1}^{N} \varphi_i \lambda_i, \varphi_i = (1 - \lambda_i) \frac{1}{\sum_{i=1}^{N} (1 - \lambda_i)}$$

(4)

Where $\varphi_i$ is the weight factor of the validity of line $i$, which can highlight the impact of lines with low utilization validity on the operation validity of the whole grid.

3) Volatility adaptability index $f_{OA}$. It reflects the weighted average of the power volatility of the whole lines. The smaller the index is, the smaller the disparity between the practical operating status and the average operating status of the system is, the more interference resistant the grid is.

$$f_{OA} = \sum_{i=1}^{N} \varepsilon_i V_i, \varepsilon_i = V_i \frac{1}{\sum_{i=1}^{N} V_i}$$

(5)

Where $\varepsilon_i$ is the power volatility ratio weight factor of line $i$, which can highlight the influence of the lines which have large power volatility to the whole grid.

3. The Generator Capacity Adaptability and Adaptability Index

3.1. The Generator Capacity Adaptability

The main factor affecting the supply-demand balance is the randomness of renewable energy output of system with high-proportion renewable energy. The randomness includes predictable output fluctuations and prediction errors.

$$P_{R,t} = P_{R,t}^0 + P_{R,t}^e$$

(6)

Where $P_{R,t}$ is actual output of renewable energy, $P_{R,t}^0$ and $P_{R,t}^e$ are prediction value and prediction error of renewable energy output, respectively.

Adaptability of generator capacity is defined as the reserve capacity and regulating rate of the system, which can be improved through the construction of fast regulating units so as to meet the power demand caused by the volatility and prediction error of renewable energy.

In this paper, the interval prediction model is used to analyse the impact of output fluctuation and forecast error of renewable energy on the supply-demand balance and renewable energy consumption. Take wind power as an example to illustrate. Figure 1 shows the predicted wind power output under a certain confidence interval from $t-1$ to $t+1$. The randomness of wind power output can be represented by one deterministic scenario $\{P_{W,t-1}, P_{W,t}, P_{W,t+1}\}$ and two limiting scenarios $\{\overline{P}_{W,t-1}, \overline{P}_{W,t}, \overline{P}_{W,t+1}\}$ and $\{\underline{P}_{W,t-1}, \underline{P}_{W,t}, \underline{P}_{W,t+1}\}$. $\overline{P}_{W,t}$ and $\underline{P}_{W,t}$ are cap and floor limit of the actual output when the prediction error remains maximum [12]. The limiting scenario reflects the impact of the maximum prediction error on the supply-demand balance. The higher the confidence of interval prediction is, the larger the maximum forecast error (which is also called the range of confidence interval) is [13].

![Figure 1. Wind power interval prediction and analysis of scenarios.](image-url)
At any given time \( t \), a maximum forward prediction error occurs in wind power forecasting, so the system is required to have a downward reserve capacity \( W(t) \), otherwise wind curtailment will not be avoided. On the contrary, load shedding will cause. From time continuity, the variation of wind power output in the limiting scene is the most drastic due to the prediction error. Take the limiting scenario \( \{W(t), \overline{W}_{t+1}\} \) from \( t-1 \) to \( t \) as an example. If the downward regulation rate of regulating units is less than the increase of wind power output \( \overline{W}_{t+1} - W_{t} \), wind power will be curtailed. On the contrary, load shedding will cause. In summary, the interval prediction model can reflect the adequacy of reserve capacity and regulating rate under extreme operation state.

### 3.2. The Generator Capacity Adaptability Index

The regulating units should ensure that there is no wind curtailment or load shedding under most scenario based on the above analysis. At the period \( (t, t+1) \) in the limiting scenario, the maximum upward and downward regulation power requirements caused by the change of wind power output are as follows:

\[
D_u = \overline{W}_{t} - W_{t+1} \\
D_d = W_{t+1} - \overline{W}_{t}
\]

Where \( D_u \) and \( D_d \) are the maximum upward and downward regulation power requirements. The regulation capacity of the regulating units is determined by their operating state and regulation level. The regulation capacity of the regulating units can be expressed by the upward and downward power they can provide from \( t \) to \( t+1 \).

\[
S_u = \min \{R_G^+ \cdot \Delta t, \overline{P}_{G_{t+1}} - P_{G_t}^{\text{max}}\}, \\
S_d = \min \{R_G^- \cdot \Delta t, P_{G_t}^{\text{min}} - P_{G_t}^-\}
\]

Where \( S_u \) and \( S_d \) are the upward and downward regulation power of regulating units during the period, \( R_G^+ \) and \( R_G^- \) are the rates of upward and downward regulation power of regulating units, \( \Delta t \) is the time scale, \( P_{G_t}^{\text{max}} \) and \( P_{G_t}^{\text{min}} \) are actual, maximum and minimum output of regulating units at time \( t \).

If the requirement \( S \geq D \) is met, which means the adaptability requirements of the supply-demand balance is met, there will be no wind curtailment or load shedding in this period. The methods of calculating wind curtailment and power shortage in limiting scenarios are as follows:

\[
P_{W_u} = \int_{t+1}^{t+1} (D_u - S_u)dt, \quad P_{W_{t+1}} > P_{W_t} \\
P_{L_u} = \int_{t}^{t+1} (D_u - S_u)dt, \quad P_{W_{t+1}} < P_{W_t}
\]

Where \( P_{W_u} \) is curtailed wind power, \( P_{L_u} \) is the power shortage during the period \( t \). The index which reflects the adaptability of generator capacity is established based on the supply-demand balance.

Supply-demand adaptability (SDA) index \( f_{SDA} \) is shown as follows:

\[
f_{SDA} = \frac{\sum T_{\text{w}}}{{T}_{total}}
\]

Where \( T_{\text{w}} \) is the period with balanced supply and demand without wind curtailment and load shedding under the limiting scenario, \( T_{total} \) is the total number of periods.

### 4. The Grid-source Coordinated Planning Model Based on Adaptability Index

The adaptability index defined in this paper can characterize the adaptability of grid-construction and units regulation capacity to the grid-connected renewable energy from grid operating status and supply-
demand balance. Based on the adaptability index, a multi-objective grid-source coordinated transmission planning model is put forward. The construction location and capacity of transmission lines and regulating units are decision variables.

The planning case is carried out in typical scenes, and the regulating units are adjusted according to the power regulation requirements of renewable energy to maximize the consumption of renewable energy [14]. The operation state of the system can be extracted consequently, which can be used to calculate the adaptability index. Then the grid-construction and the configuration of regulating units are optimized by considering the investment cost and adaptability index to obtain the best planning scheme. The process reflects the impact the grid and generators planning on the operation.

The objective function of the planning model includes the total investment cost and adaptability index, and the constraints include the number of new lines and the security of grid operating. The model is as shown follows:

\[
F = \min \{F_1, F_2, F_3, F_4, F_5\} \tag{14}
\]

\[
F_i(C) = (k_1 + k_2) \sum_{i \in \Omega_i} c_i x_i + \sum_{i \in \Omega_i} c_{G,i} z_i \tag{15}
\]

\[
F_1(f_{SA}) = f_{SA} \tag{16}
\]

\[
F_2(f_{AA}) = -f_{AA} \tag{17}
\]

\[
F_3(f_{OA}) = f_{OA} \tag{18}
\]

\[
F_4(f_{SDA}) = -f_{SDA} \tag{19}
\]

Where \( k_1 = r(1 + r)^n / [(1 + r)^n - 1] \) is fund recovery coefficient, \( r \) is discount ratio, \( n \) is served years of the project, \( k_2 \) is fixed operating ratio of the project, \( \Omega_i \) is the set of new lines, \( c \) is the price of building a unit length transmission line, \( l_i \) is length of line \( i \), \( x_i \) is the number of new circuit of line \( i \), \( \Omega_{g,i} \) is the set of new units, \( c_{G,i} \) is the price of building a unit capacity regulating unit \( i \), \( z_i \) is increased capacity of regulating unit \( i \).

Equation (14) includes the vectors of the objective function. Equation (15) indicates the total investment cost. Equation (16-19) indicate the SA, AA, OA and SDA.

The constraints are shown as follows:

\[
\begin{align*}
\begin{cases}
x_i^{\min} \leq x_i \leq x_i^{\max} \\
i \in \Omega_i \\
x_i \in \mathbb{Z}
\end{cases}
\end{align*}
\tag{20}
\]

\[
\begin{align*}
\begin{cases}
-B\theta + P_{g,i} + P_{O,i} + P_{REG} = P_L \\
|P_i| \leq S_{i,\max}, i \in \Omega_L \\
|P_{g,i}| \leq S_{g,\max} \leq P^\text{max}_{g,i}, i \in \Omega_g
\end{cases}
\end{align*}
\tag{21}
\]

\[
\begin{align*}
\begin{cases}
-B^{N-1}\theta^{N-1} + P^{N-1}_{g,i} + P^{N-1}_{G,i} + P^{N-1}_{REG} = P^{N-1}_L \\
|P^{N-1}_i| \leq S^{N-1}_{i,\max}, i \in \Omega^{N-1}_L \\
|P^{N-1}_{g,i}| \leq P^{N-1}_{g,i} \leq P_{g,i}^{\text{max}}, i \in \Omega^{N-1}_g
\end{cases}
\end{align*}
\tag{22}
\]
$$-B_{i,j}^T \Theta^{j,i} + P_{G}^{i,j} + P_{\text{REG}}^{i,j} = P_{L}^{i,j}$$

$$|P_{i,j}^{s,t}| \leq S_{i,max}$$

$$P_{g,j}^{min} \leq P_{g,j}^{s,t} \leq P_{g,j}^{max}$$

$$P_{G,j}^{min} \leq P_{G,j}^{s,t} \leq P_{G,j}^{max}$$

$$-R_{g}^{-} \cdot \Delta t \leq P_{g,j}^{s,t} - P_{g,j}^{s,t-1} \leq R_{g}^{+} \cdot \Delta t$$

$$-R_{G}^{-} \cdot \Delta t \leq P_{G,j}^{s,t} - P_{G,j}^{s,t-1} \leq R_{G}^{+} \cdot \Delta t$$

(23)

Where $x_{i}^{max}$ and $x_{i}^{min}$ are the cap and floor limit of $x_{i}$. $\Omega_{e}$ is set of existing lines and new lines in grid. $P_{g,j}^{s,t}$, $P_{g,j}^{max}$ and $P_{g,j}^{min}$ are output, upper and floor limit of the output of regular unit $i$ under rated operation state. $\Omega_{g}$ is set of regular units in system under rated operation state. The superscript $N-1$ means the variable is under the state of “$N-1$”. The superscript $s$, $t$ means the variate is under the typical scenario. $\Omega_{s}$ is set of typical operation scenarios. $P_{G,j}^{s,t}$, $P_{G,j}^{max}$ and $P_{G,j}^{min}$ are output, cap and floor limit of the output of regulating unit $i$ in the scenario $s$ at time $t$. $R_{g}^{+}$, $R_{g}^{-}$, $R_{G}^{+}$ and $R_{G}^{-}$ are the rates of upward regulation and downward regulation power of the regulating units and the regular units. $\Delta t$ is the time scale. $Z$ is integer set.

Equation (20) indicates the constraint of the number of circuits of new lines. Equation (21) indicates operation state of units, lines constraints and power flow constraint under rated operation state, $\Theta$ is nodal admittance matrix, $\theta$ is the vector of node voltage phase, $P_{g}$ is the vector of output of the regular units, $P_{G}$ is the vector of output of the renewable energy units, $P_{L}$ is the vector of the load. Equation (22) indicates operation state of units, lines constraints and power flow constraint under the state of “$N-1$”. Equation (23) indicates operation state of units, lines constraints, power flow constraint and regulating rate of units constraint in the typical scenario.

5. Example Analysis

The nonlinear PCA method is used in paper [15-16] and this paper. In this paper, logarithmic centralization transformation is used to process the original data of each target. On this basis, the covariance matrix, eigenvalues and eigenvectors are obtained to form all principal components. Then calculate the information contribution rate of principal component. Finally, the final evaluation index is obtained by summing the principal components with the information contribution rate as the weight.

5.1. Parameter Settings

The method of K-means is used to form four typical scenarios of wind power output forecast based on the historical wind power output forecast data of a certain wind farm. The example system is modified on the basis of Gaver-18 system. Node 16 is set as the wind farm node, and Node 4, Node 9 and Node 17 are all treated as nodes which can be connected to new units, and Node 18 is taken as the slack node. Some specific parameters are set: the power reference value is 100MVA, the voltage reference value is 220kV, and the service life of the project is 15 years, the construction cost (CC)of transmission lines is 0.8 million yuan /km, the discount rate is 10%, the fixed operation rate of the project is 5%.

5.2. Analysis of Planning Scheme

The best planning scheme is plan 1 in Table 1, and the specific grid-construction and units construction plans are shown in Figure 2. The dashed lines indicate the new lines and the grey nodes indicate the new regulating units. The construction plan is to build two regulating units in Node 4, two regulating units in Node 9 and four regulating units in Node 17.
Table 1. Comparison of planning results.

| New Line (quantity) | CC/¥M | OC/¥K | N-1 OC/¥M | f_{EA} | f_{AA} | f_{OA} | f_{SDA} | Desired power shortage per year (MW·h) |
|---------------------|--------|-------|-----------|--------|--------|--------|---------|---------------------------------------|
| Plan 1              | 1-11(1),2-3(1),4-7(1),4-16(1),5-11(2),5-12(1),6-13(1),6-14(2),7-9(1),7-13(1),7-15(1),8-9(1),9-10(2),9-16(1),10-18(3),11-12(1),12-13(1),14-15(3),16-17(3),17-18(2) | 502.61 | 0 | 0 | 0.3333 | 0.1991 | 0.1030 | 0.8374 | 12538.90 |
| Plan 2              | 1-2(1),1-11(2),4-16(1),5-12(1),6-13(1),6-14(2),7-8(2),7-13(2),7-15(1),8-9(2),9-10(2),10-18(1),11-12(1),14-15(2),16-17(2),17-18(1) | 389.52 | 85 | 5.028 | 0.4702 | 0.4218 | 0.2553 | 0.4712 | 389332.64 |

Figure 2. Results of the planning model.

Scheme 1 is compared with the planning scheme (case 2) which only considers economic index in reference [17]. The specific data are shown in Table 1.

It can be known from Table 1 the number of new circuits is less in case 2 which aims at economic optimization, so the cost of construction is 22.5% lower than that of case 1 and the operation efficiency is higher than that of case 1. Overload lines will appear due to the lack of transmission capacity with the grid-connected renewable energy in case 2, so the security and reliability of the system cannot be guaranteed. Case 1 adds two transmission lines (9-16, 16-17) for renewable energy and more ring net is formed in the grid compared with case 2. Although the economy and the efficiency of grid operation are not dominant in case 1, the transmission capacity of grid is improved and the grid-construction becomes more reasonable. Therefore, the disturbance of renewable energy to the operating state of the system can be restrained. The simulation results show the operation state of grid in case 1 is more balanced and stable under the premise of meeting the security constraints. In addition, the construction of regulating units and the grid-construction is considered in coordination in case 1. Therefore, case 1 has better SDA and the desired annual power shortage is 96.78% lower than that of case 2. To sum up, the planning considering grid-source coordination based on adaptability index can improve the adaptability of the renewable-energy-accessed system from different aspects and meet the development trend of the grid-connected renewable energy.

6. Conclusions

This paper proposes an index system of grid-construction and generator capacity adaptability based on operation security, validity, stability and supply-demand balance to meet the demand of large-scale integration of renewable energy and improve the adaptability and flexibility of grid planning model. On the basis of the adaptability index, a multi-objective grid-source coordinated transmission planning model is proposed. The conclusions are shown as follows through the results of simulation.

1) The grid-construction adaptability index can measure the adaptability of grid-construction to the grid-connected renewable energy from the point of view of validity, security and stability.

2) The generator capacity adaptability index based on interval prediction model includes the regulation capacity and the adequacy of regulating rate. It can effectively reflect the consumption of renewable energy and the risk of load shedding.
3) Considering adaptability index of the grid-construction, generator capacity adaptability index and grid-source coordination construction in the initial stage of planning can not only ensure the security, stability and validity of the system, but also improve the ability of the system to accept renewable energy. Lastly, consequences of power line fault control is not considered in this paper, we should do more study in this part.

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