Assessment of the Impact of the Forecast Uncertainty of Wind and Photovoltaic Generation on Large-scale Power Transmission

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Abstract. In this paper, we proposed a method to assess the impact of the uncertainty of forecast error of wind and photovoltaic generation on power transmission. First, we proposed a probabilistic model to characterize the uncertainty of the forecast error and established an index system to assess the performance of the transmission system in various aspects. Second, we adopted the Latin hypercube sampling technique to obtain the expectation and the variance of the assessment indices. Third, we introduced a sensitivity method to measure the variation of the probabilistic characteristics of the assessment indices propagated from the variation of the forecast error. Finally, we used a stochastic multi-attribute decision-making method to make the ranking of all renewable power plants by the comprehensive influence of the uncertainty of forecast error on them. With this ranking, it is able to judge which renewable power plant’s forecast accuracy should be improved in order to most effectively control the error of the power transmission. The effectiveness of the proposed models and methods are briefly verified by a case.

Keywords: Forecast error; Wind power; Photovoltaic; Transmission system; Assessment index; Stochastic multi-attribute decision-making method.

1. Introduction
The forecast error of wind and photovoltaic (PV) generation directly affects the transmission power of the power system [1-2]. Therefore, how to effectively assess the impact of the forecast error of wind and PV generation on large-scale power transmission is crucial for improving the safety and the economy of power systems.

Many researches and studies have been done on the impact of wind and PV generation on the transmission system. Reference [3] analyzed the characteristics of the transmission capacity of the clustered transmission of wind and PV plants. Reference [4-6] constructed a novel re-scheduling model for the circumvention of over-dispatch and under-dispatch problems caused by forecast error of wind power, respectively. Reference [7] proposed an index system to evaluate the economic, environmental and safety performance of the power system integrated with wind power. Reference [8] presented an assessment system to evaluate the adequacy of the power system based on risk theory. Reference [9] proposed an assessment system for the operation flexibility of the system considering the uncertainty of wind power and load demand. Reference [10] further proposed a methodology for assessing the wind power admissible capacity. Reference [11] constructed an index system to quantify the impact of wind power fluctuations on the power system’s safety and reliability.

Based on the above review, there is no study on how the probabilistic characteristics of the assessment indices is affected by the uncertainty of forecast error of the renewable energy, and also no such method
to measure the impact of uncertain factors on the integrated performance of the system. Therefore, this paper presents an index system to assess the comprehensive performance of large-scale transmission systems and a method to evaluate the impact of the uncertain forecast error of all wind and PV plants on it. In Section 2, firstly a complete index system is built. Then, based on Latin hypercube sampling (LHS) and a sensitivity method, a method to calculate the impact matrix is presented. Finally, a stochastic multi-attribute decision-making method is used to obtain the ranking of the impact of all wind and PV plants. Section 3 shows the simulation results and Section 4 draws the conclusion.

2. The Index System

2.1. The Index System

To assess the impact of the uncertainty of the forecast error of wind and PV generations on large-scale power transmission plans, this paper establishes a system of indices for assessing the flexibility, the safety, the economic effect and the environmental effect of the transmission system. The content of the indices and the corresponding expressions are as follows:

2.1.1. The flexibility indices. (1) The probability of upward flexibility being not sufficient (UFNS) $P_{UFNS}$

$$\chi(A) = \begin{cases} 1, & A \text{ happens} \\ 0, & A \text{ does not happen} \end{cases}$$

(1)

$$P_{UFNS} = \frac{1}{T} \sum_{t=1}^{T} \chi\left(\left\{\Delta P_{L,t} > 0\right\}\right)$$

(2)

where $\Delta P_{L,t}$ is the amount of renewable energy curtailment at time $t$. $T$ is the length of scheduling time.

(2) The amount of UFNS $E_{UFNS}$

$$E_{UFNS} = \sum_{t=1}^{T} \Delta P_{L,t}$$

(3)

(3) The probability of downward flexibility being not sufficient (DFNS) $P_{DFNS}$

$$P_{DFNS} = \frac{1}{T} \sum_{t=1}^{T} \chi\left(\left\{\Delta P_{r,t} > 0\right\}\right)$$

(4)

where $\Delta P_{r,t}$ is the amount of load shedding at time $t$.

(4) The amount of DFNS $E_{DFNS}$

$$E_{DFNS} = \sum_{t=1}^{T} \Delta P_{r,t}$$

(5)

2.1.2. The safety indices. (1) The average load shedding rate $R_{\text{shed}}$

$$R_{\text{shed}} = \frac{1}{T} \sum_{t=1}^{T} \frac{\Delta P_{L,t}}{P_{L,t}}$$

(6)

where $P_{L,t}$ is the total amount of load at time $t$.

(2) The amount of overload of transmission lines $R_{\text{over}}$

$$R_{\text{over}} = \sum_{t=1}^{T} \sum_{l=1}^{N_l} \max\left(0, \frac{P_{l,t} - P_{l,max}}{P_{l,max}}\right)$$

(7)
where $P_{ij}$ is active power of the $l$-th transmission line of the system at time $t$. $P_{l}^{\text{max}}$ is the maximum active power of the $l$-th transmission line. $N_{l}$ is the number of transmission lines.

### 2.1.3. The economic effect indices.

1. The amount of electricity transmitted on a selected section $P_{\Omega}$

$$P_{\Omega} = \sum_{i=1}^{T} \sum_{l \in \Omega} P_{ij}$$

where $\Omega$ is the set of transmission line belong to the selected section.

2. The penalty cost of renewable energy generation curtailment $F_{\text{recy}}$

$$F_{\text{recy}} = C_{\text{recy}} \sum_{i=1}^{T} \Delta P_{ij}$$

where $C_{\text{recy}}$ is the unit penalty cost of renewable energy curtailment.

3. The penalty cost of load shedding $F_{\text{shed}}$

$$F_{\text{shed}} = C_{\text{shed}} \sum_{i=1}^{T} \Delta P_{Lij}$$

where $C_{\text{shed}}$ is the unit penalty cost of load shedding.

4. The total cost of power generation plan $F_{\text{total}}$

$$F_{\text{total}} = \sum_{i=1}^{T} \sum_{g=1}^{N_{G}} f \left( P_{g,i} \right) + F_{\text{recy}} + F_{\text{shed}}$$

where $f \left( \cdot \right)$ is the generation cost function of conventional generators. $N_{G}$ is the number of conventional generators.

5. The average cost on the section $F_{\text{ave}}$

$$F_{\text{ave}} = F_{\text{total}} \cdot \left( P_{\Omega} \right)^{-1}$$

### 2.1.4. The environmental effect indices.

1. The coal consumption of power generation plan $G_{\text{total}}$

$$G_{\text{total}} = \sum_{i=1}^{T} \sum_{g=1}^{N_{G}} g \left( P_{g,i} \right)$$

where $g \left( \cdot \right)$ is the coal consumption function of conventional generators.

2. The average coal consumption on the section $G_{\text{ave}}$

$$G_{\text{ave}} = G_{\text{total}} \cdot \left( P_{\Omega} \right)^{-1}$$

3. The equivalent coal consumption of renewable energy $G_{\text{recy}}$

$$G_{\text{recy}} = \sum_{i=1}^{T} g \left( P_{r,i} \right)$$

4. The utilization rate of renewable energy $\eta_{\text{recy}}$
\[ \eta_{recy} = \sum_{t=1}^{T} P_{t,t} \left( \sum_{t=1}^{T} \left( P_{t,t} + \Delta P_{t,t} \right) \right)^{-1} \]  

(16)

2.2. The Probabilistic Model of the Index.

The indices in the assessment index system are all affected by the uncertainty of the forecast error of wind and PV generations. For each forecast error is considered as a random variable, the outputs, namely the indices, are also random variables. Therefore, the probabilistic characteristics of the indices, such as the expectation and the variance, needs to be calculated. The probabilistic model of indices in the assessment index system is constructed as follows:

\[ (\mathbb{E}(U), \text{Var}(U)) = f(W) \]  

(17)

where \( U \) is the vector composed of all assessment indices. \( W \) is the random vector composed of the forecast error of all wind and PV generations in each time period; \( f(\cdot) \) is the implicit function between the expectation and the variance of the assessment indices and the forecast error of wind and PV generations. Denote “dim” as the dimension of \( W \) and “DIM” as the dimension of \( U \).

The steps to calculate the expectation and the variance of \( U \) are stated as follows:

i. Generate the original LHS sampling points \( \left( x_{1}^{1}, x_{2}^{1}, \ldots, x_{\text{dim}}^{1} \right) \ldots \left( x_{1}^{N}, x_{2}^{N}, \ldots, x_{\text{dim}}^{N} \right) \), where \( N \) is the number of sampling points.

ii. Transform the original LHS sampling points into the forecast error points \( \left( W_{1}^{1}, W_{2}^{1}, \ldots, W_{\text{dim}}^{1} \right) \ldots \left( W_{1}^{N}, W_{2}^{N}, \ldots, W_{\text{dim}}^{N} \right) \) according to the distributions of the wind and PV generation forecast error.

iii. Calculate all \( N \) samples of output \( U^{(i)}, i=1,\ldots,N \) by applying Step iv ~ Step vi to each \( W^{(i)} \).

iv. Set the generation of all wind and PV plants as the forecast value and solve the generator status and the generations of the generators by the deterministic unit commitment scheduling.

v. In each time period, use the forecast value of the renewable generations obtained by step ii, the generator status and the generation of the generators obtained by step iv as the inputs to perform a DC power flow.

vi. If no transmission line overload occurs, calculate the value of all the assessment indices. Otherwise, record the value of the transmission line overload and then perform an optimal DC power flow to calculate the other assessment indices.

vii. Calculate the expectation and the variance of each assessment index by:

\[ \mathbb{E}(U_{j}) = \frac{1}{N} \sum_{i=1}^{N} U_{j}^{(i)}, \quad j = 1,2,\ldots,\text{DIM} \]  

(18)

\[ \text{Var}(U_{j}) = N/(N-1) \left[ \frac{1}{N} \cdot \sum_{i=1}^{N} (U_{j}^{(i)})^2 - \mathbb{E}^2(U_{j}) \right], \quad j = 1,2,\ldots,\text{DIM} \]  

(19)

Due to space limitation, the model of deterministic unit commitment scheduling and the optimal DC power flow are omitted in this paper. Please refer to the references to get the detailed models.

2.3. The Procedures of Calculating the Impact Matrix

After calculating the expectation and the variance of the assessment indices, the impact matrix is calculated which represents the relative impact of the variation of the distribution parameters of different wind and PV plants on the assessment indices. The procedures are as follows:

i. Calculate the expectation and the variance of the assessment indices as described in Section 3.1.

ii. Adjust the scale parameter corresponding to each wind or PV plant by \( \pm 10\% \), and then calculate the expectation and the variance of the assessment indices.

iii. Adjust the shape parameter corresponding to each wind or PV plant by \( \pm 5\% \), and then calculate the expectation and the variance of the assessment indices.
iv. Calculate the following eight vector \( \lambda_{j}^{p+10\%} \sim \xi_{j}^{p-5\%} \) for each \( j \)-th wind (or PV) plant \((j=1,2,...,N_{r})\), each vector has \( \text{DIM} \) rows and one column:

\[
\begin{align*}
\lambda_{j}^{p+10\%} &= \frac{\mathbb{E}[f(W_{j,\mu+10\%})] - \mathbb{E}[f(W_{0})]}{10\% \times \mu_{j}} \\
\xi_{j}^{p+10\%} &= \frac{\text{Var}[f(W_{j,\mu+10\%})] - \text{Var}[f(W_{0})]}{10\% \times \mu_{j}} \\
\lambda_{j}^{p-10\%} &= \frac{\mathbb{E}[f(W_{j,\mu-10\%})] - \mathbb{E}[f(W_{0})]}{10\% \times \mu_{j}} \\
\xi_{j}^{p-10\%} &= \frac{\text{Var}[f(W_{j,\mu-10\%})] - \text{Var}[f(W_{0})]}{10\% \times \mu_{j}} \\
\lambda_{j}^{p+5\%} &= \frac{\mathbb{E}[f(W_{j,\sigma+5\%})] - \mathbb{E}[f(W_{0})]}{5\% \times \sigma_{j}} \\
\xi_{j}^{p+5\%} &= \frac{\text{Var}[f(W_{j,\sigma+5\%})] - \text{Var}[f(W_{0})]}{5\% \times \sigma_{j}} \\
\lambda_{j}^{p-5\%} &= \frac{\mathbb{E}[f(W_{j,\sigma-5\%})] - \mathbb{E}[f(W_{0})]}{5\% \times \sigma_{j}} \\
\xi_{j}^{p-5\%} &= \frac{\text{Var}[f(W_{j,\sigma-5\%})] - \text{Var}[f(W_{0})]}{5\% \times \sigma_{j}}
\end{align*}
\]

where \( W_{0} \) is the random vector with initial distribution parameters as set in Step i, and \( W_{j,\mu+10\%} \) is the random vector with the scale parameter corresponding to the \( j \)-th wind (or PV) plant in all \( T \) periods increased by 10%. Other subscripts' meaning is similar. \( \mu_{j}, \sigma_{j} \) is the average value of the scale parameter, shape parameter corresponding to the \( j \)-th wind (or PV) plant among \( T \) periods, respectively.

v. Form the impact matrix \( X \) by:

\[
X = \frac{1}{8} \cdot \left( \lambda_{1}^{p+10\%} + ... + \lambda_{N_{r}}^{p-5\%} \right)^{T}
\]

where \( \lambda_{1}^{p+10\%}, \lambda_{2}^{p+10\%}, ..., \lambda_{N_{r}}^{p+10\%} \) is the combination of \( N_{r} \) vectors (\( N_{r} \) is the number of wind and PV plants). Other notations are built in the same way.

### 2.4. The Procedures of Calculating the Ranking of the Impact of Forecast Error on the Assessment Indices

Matrix \( X \) built in the former section reveals the influence of the variation of the distribution parameter corresponding to each wind (or PV) plant on each assessment index. In this section, we will obtain the ranking of \( N_{r} \) plants regarding their comprehensive impact on all assessment indices. Stochastic multi-attribute decision-making method \([12-13]\) is an effective method for evaluating the relative advantages and disadvantages of different schemes under the condition that redundancy or mutually exclusive relationship may exist among the attributes, and thus is selected to calculate the ranking.

The procedures of the stochastic multi-attribute decision-making method are stated as follows:

i. Obtain the attribute matrix \( X = [x_{ij}] \) where \( x_{ij} \) represents the \( j \)-th attribute in the \( i \)-th scheme.

ii. Calculate the predominance between two schemes for an attribute. The definition of predominance is that if \( x_{ii} \geq x_{jk} \), scheme \( i \) is predominant to scheme \( j \) for the \( k \)-th attribute. The predominance matrix of the \( k \)-th attribute is denoted as \( \Phi_{k} = [\varphi_{k}^{ij}] \), and its element \( \varphi_{k}^{ij} \) is:

\[
\varphi_{k}^{ij} = \max \left( \frac{x_{ik} - x_{jk}}{\max(x_{ik} - x_{jk}, 0)} \right)
\]

iii. Calculate the importance of the attribute set \( \lambda \) and the fuzzy measure \( g_{\lambda} \) of the attribute set.
iv. Calculate the comprehensive predominance matrix $\Phi = \begin{bmatrix} \phi^+ \end{bmatrix}$ by Choquet quadrature [14].

v. Rank the schemes by the following comprehensive advantage degree $a_i$:

$$a_i = a_i^+ \left( a_i^+ + a_i^- \right), a_i^+ = \left( N - 1 \right)^{-1} \sum_{k \in i} \phi^*_k, a_i^- = \left( N - 1 \right)^{-1} \sum_{k \in i} \phi^-_k$$

(26)

where $N$ is the number of schemes.

The ranking of the impact of forecast error on the assessment indices can be obtained using the above method whose “attribute” and “scheme” is substituted with “assessment index” and “wind (or PV) plant”, respectively.

3. Case Studies

The modified IEEE 14-bus system is taken as the experiment system and its detailed data can be referred to https://github.com/tjykm/DataForSystem. Two wind plants and two PV plants are installed in bus 4 and 5, bus 13 and 14, respectively. It is assumed that TLS distribution is chosen as distribution of all wind and PV plants. In this case, the concerned transmission section is composed of line 4-7, 4-9 and 5-6. Standard parameters are adopted for all the branches, transformers and generators. Table 1 and Table 2 show the weight $\omega$ of 15 assessment indices and the comprehensive advantage degree of the four plants, respectively, which are calculated by the proposed method. Figure 1 shows the forecast generation of the four power plants.

![Figure 1. Forecast error of power plants.](image)

| No. index | 1-4 | 5-6 | 7  | 8-9 | 10  | 11-14 | 15 |
|-----------|-----|-----|----|-----|-----|-------|----|
| weight    | 0.3 | 0.5 | 0.7| 0.2 | 0.3 | 0.2   | 0.1|

**Table 1.** The weight of each assessment index.

| No. plant | Wind 1 | Wind 2 | PV 1  | PV 2  |
|-----------|--------|--------|-------|-------|
| degree    | 0.5824 | 0.5589 | 0.5441| 0.3308|

**Table 2.** The comprehensive advantage degree.

By the Table 2, the ranking of the influence of forecast error of the wind and PV plants on the power transmission of the sector is: wind plant 1, wind plant 2, PV plant 1 and PV plant 2. Therefore, it is suggested to improve the accuracy of the forecast error of wind plant 1, wind plant 2 and PV plant 1 in order to most effectively control the error of power transmission. For PV plant 2, the requirements for its forecast accuracy can be relatively lower.

4. Conclusion

In this paper, we propose an assessment index system and a method to evaluate the impact of the uncertainty in wind or PV forecast error on the comprehensive performance of large-scale power transmission. We first establish a forecast error model and an assessment index system. Then we propose a method
based on LHS to calculate the expectation and variance of the indices. A sensitivity-based method is used to measure the effect of wind or PV forecast error’s change on the assessment indices. Finally, by utilizing the stochastic multi-attribute decision making method, the ranking of the advantage degree of impact for each wind and PV plant on the assessment index system is obtained. The ranking result can be used to guide whose forecast accuracy should be improved to most effectively control the error of power transmission. The validity of the methods in this paper is fully verified by a case.

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