Assessment of Wind Power Plant Performance in Power Grid using Analytic Hierarchy Process

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Abstract. This paper investigates the uncertainty issue of wind power and analyzes the impact of wind power on power system with the construction of wind farm on different locations. Accordingly, an approach based on analytic hierarchy process (AHP) is proposed to obtain the best site of wind power plant in power grid. The wind speed at the site for constructing wind power plant as well as the advantages of reducing loss and improving voltage profile in power system because of using the appropriate wind power are considered in the analysis. Since the wind speed is fluctuation and uncertainty, the conventional deterministic method is not proper to deal with it. The proposed approach uses a triangular LR fuzzy number to analyse these uncertain factors. A modified IEEE 30-bus system is used to test the proposed method.

1. Introduction

With the continuously increasing of environment pressure and driving of clean energy, the renewable energy sources are playing a great role in the energy revolution. Renewable energy can be produced from a wide variety of resources including solar, wind, hydro, tidal, and geothermal. By using more renewable energies to meet the energy needs, we can lower the dependence on fossil fuels and make energy production more sustainable. Among the renewable energy sources, the wind power is developing quickly in the recent years many countries. It becomes the principal energy in the global energy production.

The drive for more wind energy has spurred innovation, bringing down costs and making wind the least expensive source of new electricity generation. In addition, the number of projects deploying even more powerful and efficient wind turbines is growing. In 2018, there are 20,641 wind turbines installed in the world, and the capacity of new installed wind power is 50,617MW. The trend is still increasing. The global new installed onshore wind power capacity will reach 61.8GW in 2019 [1].

China is the leading country in the world to develop wind power. Its wind power industry has developed rapidly in the first quarter of 2019, and the capacity of new installed wind power is about 4780MW, where offshore wind power is 120MW. The wind power generation of the first quarter in China is 104 billion kWh. The most prominent Provinces are Qinghai, Henan and Hebei with the new installed capacity 680MW, 66MW and 45MW, respectively [2].

U.S. is the second country that has the largest wind energy in the world. Its new installed wind power capacity is 6,146 MW in the first quarter of 2019, which is more than the capacity of all the currently operational wind power plants in California. The rapid growth of wind power across America elevates
the country’s total installed capacity to 97,223 MW. This continues the robust growth of the industry in recent years [1].

Europe will also usher in a boom in onshore wind power development. The capacity of new installed onshore wind power will reach 14.6GW.

Currently, the top 10 countries for developing wind power in the world are China, U.S., Germany, India, Spain, England, France, Brazil, Canada, and Italy, which are shown in Figure 1 [3].

Wind energy brings tons of benefits to power industry as well as environments. However, there exist some system operation and plan issues since more and more wind energy generations connects to the power grid, which brings a lot of uncertainty of power system operation because of the fluctuation and uncertainty of wind. Some of the issues including: wind power dispatch, reactive power optimization operation, stability and reliability of power grid operation, which were demonstrated in the publication [4-10]. In addition, improper location and construction of wind farm results in imbalance of generations and consumptions in power grid. For example in China, wind power resources are very rich but little consumed in North China, Northwest and Northeast, while they are insufficient in Southeast China. The economy and grid-connection condition are very well and the energy needs are high in the area of Southeast China. The imbalance of wind generations and consumptions leads to wind energy curtailment in North China, Northwest and Northeast [2]. Therefore, it is very important to evaluate the performance of wind power plant in power grid considering the location of wind farm as well as the advantages of regulating wind power in power systems. References [6, 11] analysed the performance of planning and operation of power grids with the connection of wind farm, but they didn’t consider the uncertainty of wind energy generation. Reference [12] handled the uncertain wind speed but ignored the influence of the wind energy to power grid operation.

This paper addresses the above mentioned issues. It studies the uncertainty issue of wind power and analyzes the impact of wind power on power system with the construction of wind farm on different locations. Then an approach based on analytic hierarchy process (AHP) is proposed to obtain the best site of wind power plant in power grid. The speed of wind at the location of constructing wind farm as well as the advantages of reducing loss and improving voltage profile in power grid because of using the appropriate wind power are considered and analyzed using a modified IEEE 30-bus system. The rest of the paper is organized as below: Section 2 Handles the uncertainty of wind power. Section 3 assesses wind power performance in power grid operation. Section 4 ranks the wind power sites using AHP method. Simulation and test analysis are reported in Section 5.

Figure 1. Comparison of wind power capacity for top 10 countries
2. Handling the Uncertainty of Wind Energy

Generally, wind energy model can be simplified as in equation (1), which is an expression to reflect the relationship of the wind power and the wind parameters [11].

\[
P_w = \frac{1}{2} \rho AC_p \eta_g \eta_b v^3
\]

(1)

Where, \(P_w\) is the wind turbine’s power output in wind power plant. \(\rho\) is the air density, which is about 1.225 kg/m\(^3\). \(A\) is the swept area of the rotor that can catch the wind. \(C_p\) is the constant of the performance of the wind turbine, which can be selected as 0.59 to 0.35 depending on the type and size of the wind turbine. \(\eta_g\) is the generating efficiency of the wind generator. \(\eta_b\) is the efficiency of gearbox/bearings in wind farm. \(v\) is the speed of wind in meter/second.

According to equation (1), the speed of wind is a major variable. It is key factor to make the decision if the site is suitable to build a wind power plant. Since the wind speed has the features of fluctuation and random, the general deterministic method is not proper to deal with it. Fuzzy number is recommended to analyze the speed of wind. According to the membership function of a fuzzy number, the uncertain wind speed can be written as follows [13].

\[
\mu_v : R \in [0,1]
\]

(2)

The fuzzy number in equation (2) can be expressed as a LR type fuzzy number [12]. In this way, the uncertain wind speed can be described as follows.

\[
\mu_v = \begin{cases} 
L \left( \frac{x-v}{a} \right), & v \leq x, \ a > 0 \\
R \left( \frac{v-x}{b} \right), & v \geq x, \ b > 0 
\end{cases}
\]

(3)

Where, \(x\) stands for the mean value of the speed of the wind.

From equation (3), the uncertain wind speed, which is the LR type fuzzy number, can be expressed as follows.

\[
v = (x, a, b)_{LR}
\]

(4)

For simplification, a triangular LR fuzzy number, which is a special type of fuzzy number, is used in the paper. Figure 2 shows the triangular LR fuzzy number of uncertain wind speed.

![Figure 2. Uncertain wind speed with a triangular LR fuzzy number](image)

Where, \(d\) stands for the model value of uncertainty for the wind speed. \(\alpha\) stands for the inferior dispersion of uncertain wind speed. \(\beta\) stands for the superior dispersion of uncertain wind speed.

According to figure 2, the membership function of the uncertain wind speed with the expression of fuzzy number can be written as:
\[
\mu_v = \begin{cases} 
\frac{v-(d-\alpha)}{\alpha}, & \text{if } v \in [(d-\alpha), d] \\
\frac{(d+\beta)-v}{\beta}, & \text{if } v \in [d, (d+\beta)] \\
0, & \text{otherwise}
\end{cases}
\] (5)

From equation (5), the uncertain wind speed is written as
\[
v = (d, \alpha, \beta)_{LR}
\] (6)

Applying \(\lambda\)-cuts to the fuzzy number in equation (6), the uncertain wind speed can be expressed as an interval data that is another format of fuzzy number, which is shown in equation (7). The values of \(\lambda\) are within between 0 and 1.
\[
v^\lambda = \left[\lambda\alpha + (d - \alpha), (d + \beta) - \lambda\beta\right]
\] (7)

or
\[
v^\lambda = \left[v_{\min}^\lambda, v_{\max}^\lambda\right]
\] (8)
\[
v_{\min}^\lambda = \lambda\alpha + (d - \alpha)
\] (9)
\[
v_{\max}^\lambda = (d + \beta) - \lambda\beta
\] (10)

3. Assessment of Wind Power Performance

The wind resources have the characteristics of the spatiotemporal variability. For example in China, Northeast area in China has the highest wind chance, which has big annual mean value of wind speed and high power density compared with South China. The wind resources over the whole country in China in the cold season are much higher than those in the warm season. Generally, the wind resources are distributed in remote locations, which are far from the load centers (e.g. big cities), where the conditions of power grid in the big cities are also better. Therefore, it needs to identify the locations or areas that are proper for using wind power (constructing wind farm), and meeting the requirement of grid secure and economic operation for better system performance.

The uncertainty of wind speed is handled in Section 2. With \(\lambda\) - cuts of uncertain wind speed for different potential wind farms, we can rank these wind farms to identify the best location of wind farm. However, this method cannot count the contributions of different wind farms to grid operation performance. For this reason, the following two indices are selected to evaluate the performance of the grid-connected wind farms.

\[
\Delta P_L_i = \frac{(P_{L_0} - P_L(WP_i))}{WP_i} \times 100\% \quad i \in NW
\] (11)

\[
\Delta V_i = \left| \frac{\sum_j (V_j(WP_i) - V_j)}{WP_i} \right| \times 100\% \quad i \in NW
\] (12)

Where, \(WP_i\) is the generation output of the \(i\)th wind farm. \(\Delta P_L_i\) is the reduction of system power losses from use of the wind energy \(WP_i\). \(\Delta V_i\) is the improvement of system voltage profile after using the wind energy \(WP_i\). \(P_{L_0}\) is the system power losses in the grid without use or installation of wind power plant. \(P_L(WP_i)\) is the system power losses after use of the wind power \(WP_i\). \(V_j\) is the voltage value at the selected critical bus \(j\) (the critical bus is defined that its voltage magnitude is outside of the permitted
range) without installation or use of wind power plant. $V_j (WP_i)$ is the voltage value at the critical bus $j$ with use of the wind energy $WP_i$. $NW$ is the number of wind farm locations.

The values of system power losses and bus voltages in equations (11) and (12) are computed from power flow calculation.

4. AHP for Ranking Wind Power Sites

From sections 2 and 3, three indices are proposed to evaluate the performance of wind farm. They are uncertain wind speed, system loss reduction and voltage improvement. Furthermore, if we consider the relative importance of the potential locations of wind power plant, which is non-quantitative, the conventional deterministic method is hard to deal with it. This paper applies analytic hierarchy process (AHP), which is a decision-making approach, to solve this issue. AHP uses the alternative and some criteria to evaluate the performance to make a final decision [14]. To evaluate the performance of the wind power plant, and get a unified rank of wind power sites, we propose a hierarchical configuration according to the theory of AHP, which is shown in figure 3. The hierarchical configuration consists of three layers. The first layer is the final decision of wind power sites based on the unified ranking. The second layer is the selected indices for testing the performance of the wind farms. They are $PI_S$, $PI_L$, $PI_L$ and $PI_V$, in which the $PI_S$ is the non-quantitative performance index. It reflects the relative importance of the wind power locations. The elements of $PI_S$, $PI_L$ and $PI_V$ are defined as follows.

$$PI_{vi} = \frac{\sum_{i=1}^{NW} V^i_{\text{max}j}}{\max_{i} V^i_{\text{max}j}} \quad i \in NW$$  

$$PI_{Li} = \frac{\sum_{i=1}^{NW} \Delta P_L_i}{\sum_{i=1}^{NW} \Delta P_L_i} \quad i \in NW$$  

$$PI_{Vi} = \frac{\sum_{i=1}^{NW} \Delta V_i}{\sum_{i=1}^{NW} \Delta V_i} \quad i \in NW$$  

Where, $PI_S$, $PI_L$ and $PI_V$ are the performance indices to evaluate the uncertain wind speed, reduce the system losses, and improve the voltage profile, respectively.

![Figure 3. Hierarchical configuration of ranking wind power locations](image)

According to the relative importance of the wind farm locations, we can calculate the performance index $PI_S$ through forming and computing the corresponding judgment matrix. In addition, the
relationship of four performance indices A-PI is also computed from the judgment matrix. Both judgment matrices can be formed according to the 9-scale method [14].

5. Simulations
To examine the proposed approach, a modified IEEE 30 bus system is used in the paper. The data and parameters of basic IEEE 30 bus system are taken from Reference [13]. Generator units are connected at buses 1, 2, 5, 11, and 13, respectively. Assume that the power system needs to build a wind power plant to meet the demand of increasing loads, and the candidate wind farm locations are selected at buses 22, 25, 26, 27, and 30, respectively. The capacity of wind power plant is 12 MW. The uncertain wind speeds for the selected wind farms in modified IEEE 30 bus system are listed in columns 2-4 in table 1. The corresponding interval expressions of the wind speeds can be computed from equation (7) and shown in columns 5-10 in table 1, where 0.85, 0.9 and 0.95-cut are applied, respectively. In table 1, columns 5-6 are the wind speeds corresponding to 0.85-cut, columns 7-8 are the wind speeds corresponding to 0.9-cut and columns 9-10 are the wind speeds corresponding to 0.95-cut. The higher the value of \( \lambda \)-cut, the smaller the interval value of wind speed. Thus, the performance index \( P_l \) can be computed from equation (13). If 0.95-cut is selected, the calculation results of the performance index \( P_l \) are shown in column 11 in table 1.

| Wind farm site | \( v \) (a) | \( v \) (d) | \( v \) (b) | \( v_{0.85}^{\min} \) | \( v_{0.85}^{\max} \) | \( v_{0.9}^{\min} \) | \( v_{0.9}^{\max} \) | \( v_{0.95}^{\min} \) | \( v_{0.95}^{\max} \) | Index \( P_l \) |
|---------------|--------------|--------------|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|
| Bus 22        | 2.1          | 7.8          | 2.3          | 7.485           | 8.145           | 7.590           | 8.030           | 7.695           | 7.915           | 0.2156           |
| Bus 25        | 2.1          | 6.8          | 2.2          | 6.485           | 7.130           | 6.590           | 7.020           | 6.695           | 6.910           | 0.1882           |
| Bus 26        | 2.8          | 6.2          | 2.9          | 5.780           | 6.635           | 5.920           | 6.490           | 6.060           | 6.345           | 0.1728           |
| Bus 27        | 1.8          | 8.1          | 3.1          | 7.830           | 8.565           | 7.920           | 8.410           | 8.010           | 8.255           | 0.2248           |
| Bus 30        | 1.2          | 7.2          | 1.8          | 7.020           | 7.470           | 7.080           | 7.380           | 7.140           | 7.290           | 0.1986           |

| Wind farm site | \( \Delta V(p.u.) \) | \( \Delta P L(p.u.) \) | \( PL_v \) (0.2767) | \( PL_l \) (0.4717) | \( PL_s \) (0.0750) | \( PL_v \) (0.1766) | weight | Rank |
|---------------|---------------------|---------------------|------------------|------------------|------------------|------------------|--------|------|
| Bus 22        | 0.03872             | 0.48                | 0.0877           | 0.1595           | 0.1336           | 0.2156           | 0.1476 | 5    |
| Bus 25        | 0.08819             | 0.59                | 0.1997           | 0.1960           | 0.1808           | 0.1882           | 0.1945 | 3    |
| Bus 26        | 0.11625             | 0.49                | 0.2632           | 0.1628           | 0.1779           | 0.1728           | 0.1935 | 4    |
| Bus 27        | 0.07343             | 0.58                | 0.1663           | 0.1927           | 0.2801           | 0.2248           | 0.1976 | 2    |
| Bus 30        | 0.12501             | 0.87                | 0.2830           | 0.2890           | 0.2288           | 0.1986           | 0.2667 | 1    |

The performance indices \( PL_l \) and \( PL_v \) for the candidates of wind power locations can be calculated from equations (14) and (15). The details of the calculation process are as below.

Through computing the power flow for the modified IEEE 30 bus system without use wind farm at any site, the buses with high and low voltage are filtered out that are selected as critical buses. Meanwhile, the initial system power losses and the initial voltage values on the critical buses are recorded. Then with installing wind farms at these critical buses, respectively, the voltage improvements at the critical buses and the system power loss reduction are computed from equations (11)-(12), and shown in columns 2 and 3 in table 2. Accordingly, the performance indices \( PL_l \) and \( PL_v \) can be calculated from equations (14) and (15), which are demonstrated in columns 4 and 5 in table 2, where the normalization values are used. According to the relative importance of the candidate sites, we can
also get the normalized performance index $PI_s$, which are shown in column 6 in table 2. Through forming the judgment matrix A-PI, the weighting factors can be computed, that is, 0.2767, 0.4717, 0.0750, and 0.1766, which is corresponding to the indices $PI_V$, $PI_L$, $PI_s$, and $PI_r$, respectively. With the weighting factors, the unified ranking of the wind farm sites for the best performance is obtained, which are listed in columns 8 and 9 in table 2. It can be observed from table 2 that the best location for building the wind power in the test system is at bus 30.

6. Conclusions
This paper first handles the uncertainty issue of wind power, especially uncertain wind speed based on fuzzy set theory, where the triangular LR fuzzy number is used to deal with the uncertainty. Then, it analyzes the impact of wind power on power system with the construction of wind farm on different locations. Furthermore, a comprehensive approach is proposed to determine the best location for constructing the wind power plant in power grid. The proposed approach is based on fuzzy set theory and analytic hierarchy process (AHP) through setting up a hierarchical configuration for ranking wind farm locations and computing the corresponding performance indices. The paper considers the wind speed of potential wind farm sites, as well as the advantages of reducing the power loss and improving the voltage profile from using the wind power. The IEEE 30-bus system with some modification is used to show the effectiveness of the proposed method.

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