Optimization of Wind Fan Selection and Operation Maintenance in the Wind Power Stations

Qinghua Liu*
Beijing Information Technology College, General Competencies Development Department, Beijing, China

* Corresponding author e-mail: liuqinghua@bitc.edu.cn

Abstract. In order to assess the wind energy resources and their utilization of wind power stations, it analyze wind speed probability distribution, the average wind speed, average wind power density, effective utilization time of wind energy, the wind power output ratio, and concludes that the wind energy level of this wind farm is between "available area" and "suboptimal area", where the effect of applying to the grid wind power is not good, and the power generation efficiency is only 19.34%. Use capacity coefficient to discuss the matching of wind energy resources and the fan, determines the new fan type III is the highest effective utilization of wind energy resources. From the two goals of balanced assignment and good economic benefit, programming model is established, which gives the schedule of maintenance personnel and the maintenance plan of the fan.

1. Introduction
Among the many new energy sources, wind power has a unique natural advantage. As a clean and non-pollution renewable energy, wind energy is one of the most widely used energy sources for development and utilization. Under the background of world energy shortage, wind power as the most mature new energy has become an important energy supplement, and it is worth developing.

Problem D in 2016 CUMCM [1] is to analyze and optimize the operation of a wind farm in China, and mainly discuss three problems: 1. assess the wind energy resources of the wind farm and its utilization; Compare the new and old types of fan, and judge which is more suitable; 3. Set up a reasonable schedule of maintenance personnel and fan maintenance plan, in order to ensure that the wind farm has better economic benefits.

2. Assessment of wind energy resources and its utilization
According to the national standard "wind energy resource assessment method of wind farm", the wind energy resources and their utilization need to be evaluated by wind energy resource parameters such as the average wind speed, the average wind power density, the effective utilization time of wind energy and the ratio of wind power output to the wind farms, and then the wind energy resources can be classified [2].
2.1. Approximate calculation of wind speed distribution

From the annex data, the wind speed distribution is known as a positive partial distribution, and the common Waybill distribution [3] is used to fit. The Waybill probability distribution model and its probability distribution density function can be expressed as:

\[ F(v) = \int_{0}^{\infty} f(v)dv = 1 - e^{\left(\frac{v}{c}\right)^{1/k}} \] (1)

\[ f(v) = k \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{1/k}} \] (2)

Where \( v \) is the wind speed, \( c \) is the scale parameters of the distribution, and \( k \) is the shape parameters of the distribution. Here we use statistics (mean value \( \mu \), standard variance \( \sigma \)) to estimate the shape parameter \( K \) and the scale parameter \( C \) of the Waybill distribution [3]:

\[ k = \left(\frac{\sigma}{\mu}\right)^{1.086} \] (3)

\[ c = \frac{\mu}{\Gamma\left(1 + \frac{1}{k}\right)} \] (4)

Put the annual wind speed data in it and obtain \( k = 2.21, c = 6.40 \), and the corresponding Waybill distribution curve is shown in Figure 1.

![Figure 1. Waybill distribution curve of wind speed.](image)

2.2. Assessment of wind energy resources

2.2.1 Average wind speed. The average wind speed is the parameter that can best reflect the local wind energy resources. Due to the randomness of wind speed, the long-term observation data are closer to the actual wind energy, so the annual average wind speed can better show the advantages and disadvantages of wind energy resources. After calculation, the average annual wind speed is \( \bar{v} = 5.67 \).

2.2.2 Wind power density. To measure the size of a local wind energy and to evaluate the potential of the wind, the wind power density is the most suitable, most convenient and most valuable. The higher the wind power density is, the better the wind energy resources is, and the higher the utilization of wind energy is. The wind power density is directly proportional to the air density and wind speed cube, so the change of air density is negligible when the accuracy requirement is not high. Therefore, the probability density distribution of wind power density \( W \) is only determined by the probability distribution characteristics of wind speed. The wind power density can be calculated by the next formula [4]:

\[ P = \frac{1}{2} \rho v^3 \]
\[ \pi = \frac{1}{2} pc^3 \Gamma(\frac{3}{k} + 1) \] (5)

So, the annual average wind power density is 204.1685 W/m².

According to China's wind power density scale and wind energy partition table issued by the state authority [5], the wind energy resources of the wind farm can be classified. The measured height of the wind speed was not given in the annex, we can estimate the wind energy level of this wind farm is between the "available area" and “suboptimal area", but for its application in grid connected wind power generation, wind energy utilization is smaller than rich area. Therefore, we conclude that the wind energy resources of the wind farm do not reach a rich level, but it can still be used.

2.3. Assessment of the utilization of wind energy resources

2.3.1 The utilization rate of wind energy resources. The utilization ratio of wind energy resources, or the effective utilization of wind energy resources, is the ratio of the effective utilization hours \( T \) of annual wind energy to the annual total hours,

\[ A = \frac{T}{8760} \] (6)

The effective utilization time of wind energy refers to the cumulative hours of wind speed in a period of time which the wind speed is in the effective wind speed range. Because the output power is 0 when the wind speed is less than or equal to a specified value, in other words, the generator fan is not rotate, which shows that wind energy in this wind speed cannot be used by the wind fan. The effective wind speed is the wind speed range from the cut-in wind speed to cut-out wind speed.

This paper selected the effective wind speed range as 3m/s-25m/s to evaluate the wind energy resources. By calculating the effective utilization hours of annual wind energy, the utilization rate of wind energy resources is 85.40%.

Similarly, the utilization rate of monthly wind energy resources can be calculated by using the ratio of the effective utilization hours of month wind energy to the total hours of each month to, see figure 2:

![Figure 2. Variation tendency of the monthly effective utilization time of wind energy.](image)

2.3.2 The actual utilization rate of wind energy resources. The actual utilization of wind energy resources \( \eta \) is to measure the power of wind fan, or is named the output ratio of wind power. It can be obtained by the ratio of the average annual output power \( P \) to the installed capacity of the fan \( P_0 \). The data of Annex 1 can be used to calculate the average annual output power of 38.39MW. Annex 3 gives the wind farm produced 25 fans in first-stage project and 99 fans in second-stage project, which the rated power is 2000kW and 1500kW, respectively. So get
In the same way, the actual utilization rate of monthly wind energy resources is calculated as Figure 3:

\[
\eta = \frac{P}{P_0} = \frac{38.39}{2000 \times 25 + 1500 \times 99} = 19.34\% \quad (7)
\]

The annual utilization rate of wind energy in the wind farm is 85.40%, while the actual utilization rate of the whole year is only 19.34%. This indicates that the wind power utilization in the wind farm is not very good, which is consistent with the previous assessment of wind energy resources.

At the same time, the highest rate of the actual utilization of wind energy resources is 28.63% in January, and the lowest is 10.98% in July. In winter (December to February) has the highest rate, followed by the spring (March to May), and again in autumn (September to November again), in summer (June to August) has the lowest rate. Therefore, the wind power utilization of the wind farm in winter and spring have more potential, which is more suitable for wind power generation, while the autumn and summer wind energy potential is relatively small, wind power can be used as an effective supplement.

From the comparison of the utilization rate of wind energy resources and the actual utilization rate, there were significant differences in December, April, July and September. In December and April, the effective utilization time is less, but the actual electricity output ratio is higher. In July and September, the effective utilization time is much, but the actual electricity output ratio is low. It may be the monthly wind speed is different, causing the wind energy to be centralized and unstable.

3. The Model of fan selection
In the construction of wind farms, the selection of wind fan with reliable operation, high efficiency, good control and good power supply is very important, which is directly related to the utilization of wind power in wind farms. Corresponding to the same wind farm, we should select wind fan by the characteristics of each observation point at different observation points, rather than select the same type.

3.1. The establishment of the model
In order to respond more accurately to the economy of the wind farm we choose the capacity coefficient as a measure of wind power to select the appropriate type of fan [6]. The greater the annual average capacity coefficient of the wind farm, will result in the better economy, and the annual average utilization rate of the fan will be higher.

Capacity coefficient of wind farm is the ratio of the actual generating capacity to the rated power of the wind farm within a certain period of time, it is also the ratio of the annual average output power \( P_a \) to the rated power \( P_r \) of the fan, that is,
According to the relationship between the power and the wind speed in Annex 3, the next formula is obtained.

\[
P(v) = \begin{cases} 
0, & 0 \leq v < v_i, \\
\eta(v)P_r, & v_i \leq v < v_c, \\
P_r, & v_c \leq v < v_r, \\
0, & v > v_r 
\end{cases}
\]  

(10)

where, \(v_i\) is the cut-in wind speed of the wind fan, \(v_r\) is the rated wind speed, \(v_c\) is cut-out wind speed, \(\eta(v)\) is the ratio of the output power and the rated power when the wind speed is between \(v_i\) and \(v_c\), which is a complex function related to the wind speed and it can reflect the output characteristic of the fan.

There are three functions that approximate the output characteristics of the fan: linear function, quadratic function and cubic function, which can be expressed respectively.

\[
\eta_l(v) = \frac{v-v_i}{v_r-v_i}, \eta_q(v) = \frac{(v-v_i)^2}{(v_r-v_i)^2}, \eta_c(v) = \frac{(v-v_i)^3}{(v_r-v_i)^3}
\]

According to the curve shape of the relationship between the output power of the fan and the wind speed and the result of the fitting, it is the cubic function relation, so we choose \(\eta_c(v)\) to calculate, put the output characteristic of the fan \(\eta_c(v)\) and wind speed probability density function \(P_v(v)\) into the annual average output power formula, then get:

\[
P^c = \frac{P_r}{(v_r-v_i)} \int_{v_i}^{v_r} (v-v_i)^3 P_v(v)dv + P_r \int_{v_r}^{v_c} P_c(v)dv
\]  

(11)

3.2. The solution of the model

According to the wind speed of six fans provided in Annex 2, we can get the mean and standard deviation of annual mean wind speed, and the characteristic parameters of wind speed obeying Waybill distribution, as shown in Table 1:

|     | 4# | 16# | 24# | 33# | 49# | 57# |
|-----|----|-----|-----|-----|-----|-----|
| \(\mu\) | 6.32 | 6.07 | 5.74 | 5.65 | 6.08 | 6.20 |
| \(\sigma\) | 3.27 | 3.32 | 3.45 | 2.98 | 3.39 | 3.62 |
| \(k\) | 3.10 | 2.86 | 2.79 | 2.99 | 2.77 | 2.55 |
| \(c\) | 7.07 | 6.81 | 6.45 | 6.33 | 6.83 | 6.98 |

Through previous discussions, it has been known that the design parameters of wind fan and the data of wind energy at the selected observation points directly determine the size of the capacity coefficient. The MATLAB program is written to calculate the capacity coefficient of each observation point for each fan type, such as table 2:
Table 2. Capacity coefficient of each observation point matching each fan type.

| Fan type | 4# | 16# | 24# | 33# | 49# | 57# |
|----------|----|----|----|----|----|----|
| Fan type I | 0.2205 | 0.2036 | 0.1856 | | | |
| Fan type II | 0.2465 | 0.2274 | 0.2065 | 0.1816 | 0.2304 | 0.2461 |
| Fan type III | 0.2025 | 0.2036 | 0.1856 | 0.1599 | 0.2068 | 0.2227 |
| Fan type IV | 0.1970 | 0.1820 | 0.1666 | 0.1406 | 0.1854 | 0.2014 |

The six observation points, the capacity coefficient calculated differences by using different types of fans, where the capacity coefficient of type III is greater than the original type (type I and type II) in first-stage project and second-stage project; the capacity coefficient of type IV is equal or not quite different to type I in first-stage project, but it is greater than type II in second-stage project; the capacity coefficient of type V models is less than type I in first-stage project, and it is greater than type II in second-stage project. It can be seen that considering the wind energy resources and fan's matching angle, the capacity coefficient of each fan type is ranked as follows:

Type III > type I = type IV > type V > type II

Therefore, without considering the cost and maintenance cost of each fan type, the original type (type I, type II) can be replaced with type III. If the cost of type III is higher, the original model can be replaced by the type IV or V in second-stage project, accordingly increasing the effective utilization of wind energy resources. To sum up, the new type fan is more suitable than the existing wind fan under the existing wind energy resources.

4. planning model for maintenance scheduling

For safety production needs, fans need two times of shutdown maintenance every year, and the continuous working time between two maintenance is not more than 270 days. Each maintenance needs a group of maintenance personnel to work 2 days continuously. At the same time, the wind farm needs a group of maintenance personnel to be on duty every day to deal with emergencies. The four groups of maintenance personnel in the wind farm can be engaged in duty or maintenance work, and the continuous working hours (on duty or maintenance) for each group of maintenance personnel are not more than 6 days. In order to ensure that the wind farm has better economic benefits and keep the work tasks of the maintenance personnel relatively balanced, a reasonable schedule and fan maintenance plan will be made to maximize the benefit.

According to the requirements, a programming model can be established for the schedule of maintenance personnel and the maintenance plan of the fan. 0-1 variables are introduced:

\[
x_{ik} = \begin{cases} 
1, & \text{group } i \text{ work(maintenance or duty) on the } k-\text{th day} \\
0, & \text{group } i \text{ is not working on the } k-\text{th day} 
\end{cases}
\]

\[
y_{jk} = \begin{cases} 
1, & \text{the } j-\text{th fan work on the } k-\text{th day} \\
0, & \text{the } j-\text{th fan is not working(in maintenance) on the } k-\text{th day} 
\end{cases}
\]

Where, \( i = 1,2,3,4 \) is the group of the maintenance personnel, \( j = 1,...,124 \) is the number of the fans, \( k = 1,...,365 \) is the number of days per year.

The objective function to measure the relatively balanced task of the maintenance personnel of each group can be expressed as:

\[
\min \{ \max \| m_i - m_j \| + \max \| m_i \| \} 
\]  

(12)
$m_i = \sum_{k=1}^{365} x_{ik}$ Express the one year working time (including maintenance and duty) of maintenance personnel of group $i$, $\max|m_{\max} - m_{\min}|$ express the difference between the maximum working time and the minimum working time in each group.

The objective function to measure the good economic benefit of the wind farm can be expressed as:

$$\min \left\{ \sum_{j=1}^{124} \sum_{k=1}^{365} p_k (1 - y_{jk}) \right\}$$

$p_k = \frac{P}{124}$ Express the output power of each fan on the day $k$ (assuming that the output power of each fan is constant).

The following constraints can be obtained from the requirements in the question:

1) One group of maintenance personnel must be on duty every day to respond to emergencies:

2) The continuous working hours (on duty or maintenance) for each group of maintenance personnel are not more than 6 days:

3) The time interval between the two maintenance of the fan is not more than 270 days.

4) One group of maintenance personnel should be operated for 2 days for each maintenance of the fan:

To sum up, the programming model can be obtained.

$$\min \left\{ \max|m_{\max} - m_{\min}| + \max|m_{\max} - m_{\min}| + \sum_{j=1}^{124} \sum_{k=1}^{365} p_k (1 - y_{jk}) \right\}$$

$$\sum_{k=1}^{365} x_{ik} \geq 1, \quad k = 1,2,\ldots,365$$

$$\sum_{i=1}^{4} x_{ik} \leq 7, \quad i = 1,2,3,4, k = 1,2,\ldots,359$$

$$\sum_{j=1}^{124} y_{jk} \leq 270, \quad j = 1,2,\ldots,124, k = 1,2,\ldots,95$$

$$\sum_{j=1}^{124} (1 - y_{jk}) x_{ij} = 2, i = 1,2,3,4, j = 1,2,\ldots,124, k = 1,2,\ldots,364$$

By using LINGO software, we can get the scheduling plan for each group of maintenance personnel in one year and the maintenance plan for each fan. Table 3 gives some results of maintenance personnel’s work, rest and maintenance in July and Figure 4 show the number of working days and maintenance days per month for the maintenance personnel of each group.

**Table 3. Schedule of maintenance personnel in July.**

| July | 182 | 183 | 184 | 185 | 186 | 187 | 188 | 189 | 190 | 191 | 210 | 211 | 212 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Group 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | ... | 1 | 0 | 1 |
| Group 2 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | ... | 1 | 0 | 1 |
| Group 3 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | ... | 1 | 0 | 0 |
| Group 4 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | ... | 1 | 1 | 0 |

Note: 1 means the maintenance personnel work (maintenance or duty), and 0 means the maintenance personnel do not work.
5. Conclusion

It can provide an important basis for wind farm site selection using wind energy resource assessment, the assessment is accurate or not related to the wind farm economic benefits. We choose parameters such as the average wind speed, average wind power density, effective utilization time of wind energy and wind power output ratio to assess, the calculated results can represent the actual wind energy resources to some extent.

It is relatively simple and accurate to use capacity coefficient to select wind fan, but different functions of the output characteristic functions has a great influence on the calculation results of the capacity coefficient. Based on the parameters of wind energy resources and fan, we use cubic function to fit and compare new and old types of fan. A multi-objective 0-1 programming model is established, which give the better schedule of maintenance personnel and the maintenance plan of the fan, with wide and good applicability.

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