Study on the Matching of the Wind Turbine Capacity and the Rotor Diameter in Inner Mongolia

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Abstract: There are abundant wind resources in Inner Mongolia Autonomous Region and in order to develop the wind resources economically and reasonably, it is necessary to produce and promote wind turbine generators that fit the exploitation of the wind resources. The energy generated by the wind turbines is closely linked to the rotor swept area. If the rotor diameter doubles, the wind power will increase by four times. This paper, based on the actual wind resources, divided Inner Mongolia into different regions, and, in accordance with the present wind farm development in Inner Mongolia and the on-grid energy requirements, offered a scheme for the matching of the unit capacity and the rotor diameter in wind farms of some typical regions, which provides some scientific and theoretical references for the proper selection of the wind turbine generator parameters.

1. Introduction
Inner Mongolia Autonomous Region is located in the Mongol Plateau where there are 83,000 km² with the annual average wind speed of 5.5m/s, and 200,000 km² with the annual average wind speed between 4.5 and 5.4m/s. Its area for abundant wind energy ranks first in China and therefore this region is fit to develop wind power projects [1-4]. For the economic feasibility of the wind power projects, the operation of the selected wind turbine generators has to reach the required on-grid energy. The on-grid energy of the operated generators is closely linked to the local wind resources. However, due to the geographical features of Inner Mongolia Autonomous Region, which is extended from the northeast of China to the southwest, with a straight east-west distance of more than 2,400km and north-south distance of 1,700km, the wind resources are quite different in different regions. As a result, it is crucial to make regional divisions on the basis of the respective wind resources so as to develop the wind resources more reasonably and provide more reliable references for the producing, introducing, selecting, promoting and distributing of the wind turbines. Moreover, the amount of electricity produced by the wind turbine generators is closely linked to the rotor diameter. The rotor obtains energy from turbulence. According to the formula $P = 0.5 \rho Av^3$ [5], the wind power $P$ has a square relationship with the rotor diameter, so it is critical to choose the proper rotor diameter after defining the unit capacity based on the corresponding regional wind resources.

2. Regional Division for Wind Resources
Region A: regions with rich wind resources, including the northwest part of Xilinhot, the north central part of Ulanqab, the north part of Baotou and Bayannur. In these regions, the annual average value of
effective wind power density at the height of 10m ranges from 260 W/m$^2$ to 320 W/m$^2$ and the annual hours available for operation can amount to 6100~7800h, that is, the wind turbines can work for 250~325 days in a year. The annual average wind speed stability parameter $C_v$ values between 0.06 and 0.09 and the annual longest hours with continual ineffective wind speed are between 15 and 50 hours.

Region B: regions with adequate wind resources, including the east and south part of Xilinhot, the south part of Ulanqab, Baotou and Bayannur, the north part of Alxa, and the west part of Hulunbuir. In these regions, the annual average value of effective wind power density at the height of 10m ranges from 200 W/m$^2$ to 2600 W/m$^2$ and the annual hours available for operation can amount to 5250~6780h; in other words, the wind turbines can work for 220~280 days in a year. The annual average wind speed stability parameter $C_v$ values between 0.06 and 0.10, and the annual longest hours with continual ineffective wind speed varies between 30 and 70 hours.

Region C: regions with available wind resources, including southwest part of Hohhot, the whole area of Xinggan League and Tongliao City, the east part of Xilinhot, most part of Chifeng City and Ordos City, and the south part of Alxa. In these regions, the annual average value of effective wind power density at the height of 10m ranges from 100 W/m$^2$ to 200 W/m$^2$ and the annual hours available for operation are up to 4380~6100h; in other words, the wind turbines can work for 180~250 days in a year. The annual average wind speed stability parameter $C_v$ values between 0.08 and 0.13, and the annual longest hours with continual ineffective wind speed are between 40 and 100 hours.

Region D: regions with inadequate wind resources, including the northeast part of Hulunbuir, the southern part of Ordos and most part of Hohhot. In these regions, the annual average value of effective wind power density varies from 50 W/m$^2$ to 100 W/m$^2$ and the annual hours available for operation are up to 2000~4950h, which means the wind turbines can work for 80 to 200 days in a year.

3. Matching of the Unit Capacity and the Rotor Diameter

With the booming of wind power industry, Inner Mongolia, known for its abundant wind resources, is fit for constructing large-scale wind power farms. So far, many large wind farms have been built and put into operation, including Huitengxile Wind Farm, Shangdu Wind Farm, Zhurihe Wind Farm and Xilinhot Wind Farm. Now that there has been no further developing potential in Region A, the future wind farm expansion mainly focuses on areas of Region B and C. In terms of wind turbine selection, the 2MW generator system or above are not easy for inland transportation, and at the same time, as the inland wind shear is rather strong in Inner Mongolia, large diameter rotors are bound to be affected, causing low efficiency of the wind energy exploitation. As a result, it is better to choose 1.5MW and 2MW wind turbine unit models in Inner Mongolia.

Based on the current wind farm construction scheme, it can be figured out by techno-economic analysis that the optimal annual available hours of the wind turbine generator system should be up to 2,200 to 2,800 hours. If taking 2,500 hours as the standard of the annual available hours, only when the 1.5MW generator produces 5 million KW theoretical electricity in a year, and the 2.0MW generator produces 6.67 million KW, can they meet the on-grid electricity requirement. (The on-grid electricity is usually calculated as 75% of the theoretical generating power.)

Taking into account the present wind farm development, the future expansion tendency and the actual wind energy resources in Inner Mongolia, this paper chose three regions---Wulate Houqi in Bayannur City, Manchouli in Hulunbuir City, and Khorchin Youyiqianqi in Xingan League as the typical areas to determine the corresponding rotor diameter. The hub height of the selected generator model is 70m, the cut-in wind speed is 3m/s, and the cut-out wind speed is 25m/s. The rated wind speed is usually taken as 1.3~1.5 times of the mean wind speed. Choosing one rated wind speed among the value range, the rotor diameter can be worked out with the rated power. Then, it is time to test whether the wind turbine can generate enough electricity to meet the on-grid need. If it exceeds
the on-grid electricity, it signifies that the rated wind speed is higher than the chosen rated wind speed value; if on the contrary, it indicates that the rated wind speed is lower than the chosen value. The iteration is repeated with different values of the rated wind speed until the theoretical electricity is satisfied.

1) Wulate Houqi lies in Bayannur City and is about 1,400m above the sea level. With a plateau continental arid climate, this region, subject to the strong cold high atmospheric pressure from Mongolia, is windy all year round, especially in spring and winter. The wind farm 70m height representative year annual average wind speed is 8.0m/s, As shown in Table 1 and the annual average wind power density is 486.6 W/m$^2$ while the 10m height representative year annual average wind speed is 6.2m/s and the annual average wind power density is 224.1 W/m$^2$. According to the wind resources category criteria in this paper, this area belongs to Region B.

| wind speed range(m/s) | wind speed frequency(%) | wind speed range(m/s) | wind speed frequency(%) |
|----------------------|------------------------|----------------------|------------------------|
| < 0.6                | 1                      | 13.0                 | 5                      |
| 1.0                  | 2                      | 14.0                 | 4                      |
| 2.0                  | 4                      | 15.0                 | 2                      |
| 3.0                  | 7                      | 16.0                 | 2                      |
| 4.0                  | 8                      | 17.0                 | 1                      |
| 5.0                  | 9                      | 18.0                 | 1                      |
| 6.0                  | 9                      | 19.0                 | 0                      |
| 7.0                  | 9                      | 20.0                 | 0                      |
| 8.0                  | 9                      | 21.0                 | 0                      |
| 9.0                  | 8                      | 22.0                 | 0                      |
| 10.0                 | 8                      | 23.0                 | 0                      |
| 11.0                 | 7                      | 24.0                 | 0                      |
| 12.0                 | 5                      | 25.0                 | 0                      |

The annual unit power generation is the total sum of the annual average wind speed hours at the respective wind speed scale (within the range of effective wind speed) multiplying the corresponding out-put power at the respective wind speed scale. The formula [6] is as follows:

$$G = \sum N_i W_i$$ (1)

among which, $G$ (kW$h$) means the energy generation; $N_i$ (h) refers to the total number of hours of the wind speed at the respective wind speed scale) in a year; $W_i$ (kW) signifies the corresponding out-put power under the respective wind speed scale.

In Wulate Houqi, the mean air pressure is 84.08 kPa, and the annual average temperature is 8.6°C. Accordingly, the average air density $\rho$ can be calculated by the following formula:

$$\rho = P(R \times T)^{-1}$$ (2)

among which, $P$ (Pa) is the annual mean air pressure; $T$ (t°C + 273) stands for the average absolute temperature of Kelvin temperature scale in a year; $R$ is the gas constant which values 287 273 J/kg • K. By calculation, the average air density can be obtained, whose value is 1.04 kg/m$^3$.

The following is the formula for the out-put power of the wind turbine:

$$W = 0.5 \rho A v^3 c_p$$ (3)
among which, $\rho$ is the air density, $A$ is the rotor swept area, $v$ is the wind speed and $c_p$ is the rotor power coefficiency.

Through the above formula, combined with the existing market models, the respective coefficients can be determined and therefore the rotor diameter of the two selected models can be obtained to meet the on-grid electricity standards. By calculation, it is obtained that the rotor diameter of the 1.5MW wind turbine generator system is approximately 78m, and that of the 2MW generator system is approximately 90m.

2) Manchouli lies in the west of Hulunbuir, 660m above the sea level, with a rolling prairie landscape. The 70m height representative year annual average wind speed at the wind farms is 7.2m/s, As shown in Table 2 and the average wind power density is $504 \text{ W/m}^2$ while the 10m height annual average wind speed is 5.8m/s and the average wind power density is $252.4 \text{ W/m}^2$. According to the wind resources categories made by this paper, this area also falls into the category of Region B.

| wind speed range(m/s) | wind speed range(m/s) | wind speed frequency(%) | wind speed frequency(%) |
|-----------------------|-----------------------|-------------------------|-------------------------|
| < 0.6                 | 13.0                  | 2                       | 3                       |
| 1.0                   | 14.0                  | 6                       | 2                       |
| 2.0                   | 15.0                  | 6                       | 2                       |
| 3.0                   | 16.0                  | 8                       | 1                       |
| 4.0                   | 17.0                  | 10                      | 1                       |
| 5.0                   | 18.0                  | 10                      | 1                       |
| 6.0                   | 19.0                  | 9                       | 0                       |
| 7.0                   | 20.0                  | 8                       | 0                       |
| 8.0                   | 21.0                  | 8                       | 0                       |
| 9.0                   | 22.0                  | 7                       | 0                       |
| 10.0                  | 23.0                  | 6                       | 0                       |
| 11.0                  | 24.0                  | 5                       | 0                       |
| 12.0                  | 25.0                  | 4                       | 0                       |

The air density of the wind farms in Manchouli is $1.19 \text{ kg/m}^3$, so it can be calculated that the proper rotor diameter of the 1.5MW wind turbine generator system in this area is 80m and that of the 2MW generators is 92m.

3) Khorchin Youyiqianqi, located in the south of the Great Xingan Mountains in Inner Mongolia, is a hilly area with a cold temperate continental monsoon climate. In this area, the northwest wind prevails all year round. The 70m height annual average wind speed is 7.4m/s, As shown in Table 3 and the average power density is $446 \text{ W/m}^2$, whereas the 10m height annual average wind speed is 5.3m/s, and the average wind power density is $190 \text{ W/m}^2$. According to the category standard, this area belongs to the category of Region C.
Table 3. 70m height representative year wind speed frequency distribution in Khorchin YouYiQianQi

| Wind speed range (m/s) | Wind speed frequency (%) | Wind speed range (m/s) | Wind speed frequency (%) |
|------------------------|--------------------------|------------------------|--------------------------|
| < 0.6                  | 0                        | 13.0                   | 3.67                     |
| 1.0                    | 1.08                     | 14.0                   | 2.51                     |
| 2.0                    | 2.64                     | 15.0                   | 1.29                     |
| 3.0                    | 5.58                     | 16.0                   | 0.79                     |
| 4.0                    | 8.14                     | 17.0                   | 0.48                     |
| 5.0                    | 10.33                    | 18.0                   | 0.22                     |
| 6.0                    | 12.09                    | 19.0                   | 0.14                     |
| 7.0                    | 10.9                     | 20.0                   | 0.07                     |
| 8.0                    | 10.05                    | 21.0                   | 0.08                     |
| 9.0                    | 8.9                      | 22.0                   | 0.01                     |
| 10.0                   | 8.1                      | 23.0                   | 0                        |
| 11.0                   | 7.01                     | 24.0                   | 0                        |
| 12.0                   | 5.91                     | 25.0                   | 0                        |

By calculation, the wind farm air density in Khorchin Youyiqianqi is 1.2 kg/m³ and following the same calculating process as the above, it can be obtained that the appropriate rotor diameter of the 1.5MW wind turbine generator system in this area is 76m and that of the 2MW generators is 88m.

4. Conclusion
The paper divided the wind resources in Inner Mongolia into three categories and then chose two typical places from category B and one typical place from category C to study the matching of the unit capacity and the rotor diameter. With meeting the on-grid electricity as the premise, the paper calculated the corresponding rotor diameters based on the essential factors of the wind resources in the three places. By calculation, the rotor diameters of 1.5MW wind turbine generator system for wind farms in Wulate Houqi, Khorchin Youyiqianqi and Manchouli are respectively 78m, 76m, and 80m. The rotor diameters of 2MW generator system in these three regions are 90m, 88m and 92m. Moreover, it can be inferred that based on the characteristics of wind resources in these areas, the rotor diameter can be determined by choosing the rated wind speed of 10~11m/s. As a result, the appropriate rotor diameter for 1.5MW wind turbine generator system is between 76~80m whereas the rotor diameter for 2MW generator system is between 88~92m. By analysis and calculation, this study offers some theoretical basis and references for the matching of the unit capacity and the rotor diameter in Inner Mongolia wind farms.

5. References
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