Analysis and application of the relationship between wind power curve and power generation based on operating data

Pingchuan Wang1*, Yuanpeng Zhang2, Shuai Yuan2, Junen Li2, Dehua Wang3 and Yuejiao Wang3

1 Dalian University of Technology, Dalian, Liaoning Province, 116024, China
2 State Grid Shandong Power Supply Company, Jinan, Shandong Province, 25001, China
3 State Grid Shandong Electric Power Research Institute, Jinan, Shandong Province, 25002, China
*liguanglei@yjy.sd.sgcc.com.cn
*Corresponding author’s e-mail: lovexjtulgl@126.com

Abstract. Wind power curve has a certain promotion effect on increasing the power generation. Firstly, this paper analyzes various factors that affect the power curve of a wind turbine, and establishes a mathematical model of the power curve. Secondly, the relationship between wind power generation and power curve is analyzed, and the calculation formula of annual power generation is proposed. Finally, based on the data of an actual operating wind farm, a statistical analysis of annual power generation is carried out, and the power curves of two typical units is compared to analyze the causes. Through the analysis of examples, the effectiveness of the proposed method is verified, and it can provide a reference for improving the operation level of wind turbines.

1. Introduction

Wind energy has random and intermittent characteristics, which leads to the instability of wind power output. When the wind power is connected to the grid, the instability of wind power output will affect the power quality[1-2]. Wind power curve is the basis for safe and stable operation of wind power. Therefore, the establishment of an accurate wind power curve is of great significance for improving wind power generation and safe and stable operation. At the same time, the wind power curve can be used as an important reference, such as the performance assessment of wind turbines, the assessment of wind turbine generating capacity, and the loss of electricity from wind turbines.

Nowadays, the global research on the power curve of wind turbines still studies the variables in the theoretical formula according to the definition of the IEC61400-12 standard[3-4]. Some research institutions only look for methods to verify the optimization of wind turbine curves from the aspect of algorithms. At present, the wind power curve modeling methods adopted by scholars at home and abroad can be divided into four types, namely discrete methods, parametric methods, non-parametric methods and stochastic methods [5-6]. China is still in the initial stage in the research direction of wind turbine power curve. The main reason for this is the lack of grasp of the overall wind turbine research methods, such as meteorological factors, mechanical components, electrical quantities, and so on. These factors were not taken into account in the study and will lead to inaccurate results. In order to solve these
problems, the power curve analysis is carried out in this paper, and the data calculation is combined with actual cases.

2. Power curve characteristic analysis

2.1. Definition of power curve

Under standard air density, the standard power curve of a wind turbine is defined as the relationship between the output power of the wind turbine and the wind speed. Normally, when a wind turbine is shipped from the factory, the manufacturer will provide the user with a standard power curve. However, the actual operating conditions and design conditions of wind turbines are different. This situation causes the actual power curve of the wind turbine to be inconsistent with the standard power curve. Due to the uncertainty of changes in wind speed and direction, especially the complexity of mountainous terrain, there are still many difficulties in testing the power curve of wind turbines. The related test methods and standards are still being improved.

According to the standard IEC61400-12, the power curve of a wind turbine represents the relationship between the output power of the wind turbine and the 10-minute average wind speed[7-9]. Generally, wind turbine manufacturers draw power curves according to the IEC61400-12 standard at a standard air density of 1.225 kg/m³.

When the wind turbine is actually running, the wind turbine will show different output characteristics under different wind speeds. Therefore, its output characteristics can be divided into the following four stages, which is shown in the following formula.

\[
P(v) = \begin{cases} 
0, & 0 \leq v < v_{\text{cutin}} \\
\frac{1}{2} \rho S v^3 C_p, & v_{\text{cutin}} \leq v < v_f \\
P_f, & v_f \leq v < v_{\text{cutout}} \\
0, & v \leq v_{\text{cutout}} 
\end{cases}
\]  

(1)

In the above formula, \( P(v) \) represents the active output power of wind turbine, \( v \) is the wind speed of wind turbine, \( v_{\text{cutin}} \) represents the cut-in wind speed, \( v_f \) is the wind speed of wind turbine, \( S \) is the swept area of the wind wheel, \( \rho \) is the density of air, \( C_p \) represents the power coefficient, \( v_f \) is the rated speed of wind turbine, \( P_f \) represents the rated active power, \( v_{\text{cutout}} \) is the cut-out wind speed.

2.2. Influencing factors

Affected by the wind farm wind conditions and formation conditions, the power curves formed by wind turbines under different operating conditions and conditions are different. Under poor wind conditions, the power curve of an excellent wind turbine may not reach the standard value, and the power generation may be lower than other wind turbines of the same type.

There are many factors that affect the wind power curve, including wind speed, wind direction, terrain, etc. at the installation site of the wind turbine. Therefore, the power curve of a wind turbine is a group rather than a single one. In other words, with the change of external factors such as time and wind speed, the power curve of the same wind turbine will form a series of different power curves. In addition, differences in sensor accuracy, control parameters, and power curve generation software for wind turbines will also cause differences in the actual operating power curves of the units.

Based on the above analysis, in the case of these same factors, using a longer time to form a more complete power curve, operating personnel can compare the actual operating efficiency of different units. At the same time, under the comprehensive consideration of many factors affecting the number of power curves, the power curves formed by different units in a wind farm can be compared, and the actual performance of the units can be roughly examined.
2.3. The relationship between power generation and power curve
Affected by the wind farm wind conditions and formation conditions, the power curves formed by wind turbines under different operating conditions and conditions are different. Under poor wind conditions, the power curve of an excellent wind turbine may not reach the standard value, and the power generation may be lower than other wind turbines of the same type.

The annual power output of a single wind turbine is the sum of the annual average wind speed hours and the wind turbine output power performance. The calculation formula is shown below.

\[ G = \sum N_iW_i \]  

(2)

In the above formula, \( G \) represents the annual power generation of the wind turbine, \( N_i \) represents the annual accumulated hours corresponding to the corresponding wind speed level, \( W_i \) is the output power corresponding to the wind speed of the wind turbine.

According to the above formula, the annual power generation of a wind turbine can also be derived and calculated based on the power curve of the unit and the wind frequency of the position. However, the power curve of the wind turbine used in the calculation must be provided by the manufacturer. At the same time, this power curve must be determined by an authoritative organization. On the other hand, the actual operating power curve of the wind farm unit can also be calculated from the annual power generation of the unit and the wind frequency of the unit.

3. Typical case analysis

3.1. Annual power generation statistics
The wind farm studied in this paper is located in Yantai, Shandong Province. The location of this wind power site has excellent power generation resources. The total installed capacity of the wind farm is 99MW. The units are all of a certain type of permanent magnet direct drive variable pitch 1.5MW. The diameter of impeller is 82m. According to wind data from the wind farm, the air density in this area is 1.226kg/m³, and the average annual wind speed at the height of 70m is 7.4m/s.

The wind farm studied in this paper is located in Yantai, Shandong Province. The location of this wind power site has excellent power generation resources. By analyzing the annual power generation of wind turbines, it is found that there is a difference in the average annual power generation between them. The average annual power output of some wind power generating units is about 10% higher than that of the average unit. The owner of the wind farm believes that the power curve problem is the root cause of the low power generation of some units. Therefore, the wind turbine cannot be guaranteed on schedule.

3.2. Comparison of power curves
As shown in Table 1, comparing the power curve operation data of the 3 # and 16 # units, it is found that the power curve formed by the 3 # unit is better than the 16 # unit when the wind speed is lower than 13 m/s. However, from the statistics of the power generation of the two units, in most cases the annual power generation of the 3 # unit is lower than that of the 16 # unit. From this point of view, the level of the unit's annual power generation is not entirely determined by the power curve.

| Number of wind turbine unit | Wind speed (m/s) | Active power (kW) | Number of wind turbine unit | Wind speed (m/s) | Active power (kW) |
|---------------------------|-----------------|-------------------|---------------------------|-----------------|-------------------|
| 3 #                       | 3.15            | 83                | 16 #                      | 3.15            | 71                |
| 3 #                       | 3.65            | 168               | 16 #                      | 3.65            | 146               |
| 3 #                       | 4.15            | 178               | 16 #                      | 4.15            | 159               |
| 3 #                       | 4.65            | 201               | 16 #                      | 4.65            | 192               |
| 3 #                       | 5.15            | 296               | 16 #                      | 5.15            | 273               |
From the above data analysis, wind turbines in the same wind farm have different wind conditions due to different locations. There are some deficiencies and limitations in comparing unit performance through actual operating power curves. But only from the power curve generated by the operation of the unit, the actual power generation of the wind turbine is also different.

4. Conclusion
This paper analyzes the definition and influencing factors of power curve of wind turbine. By analyzing the annual operation data of a wind farm, the power curve of the wind turbine has a certain relationship with the power generation, but it is not necessarily related to the level of wind turbine power generation. There are many factors that affect the wind power curve, so it is difficult to accurately evaluate the performance of the unit simply through the field unit operating power curve. For this reason, when operators analyze the reasons for insufficient power generation, it is necessary to comprehensively and reasonably evaluate the effect of the wind power curve so as to avoid unnecessary economic losses.

Acknowledgments
This work was supported by Science and technology project of State Grid Corporation of China.

References
[1] Yang, Wenxian., Tavner, P J., et al. (2014) Wind turbine condition monitoring : Technical and commercial challenges. Wind Energy, 17:673-693.
[2] Li, Jian., Lei, Xiao., et al. (2014) Normal behavior models for the condition assessment of wind turbine generator systems. Electric Power Components and Systems, 42:1201-1212.
[3] Yan, Yonglong., Li,Jian., et al. (2014) Condition parameter modeling for anomaly detection in wind turbines. Energies,7:3104-3120.
[4] Guo, Peng., Liu,Lin. (2018) Modeling and Monitoring of Multivariable Wind Turbine Power Curve. Power System Technology,42:3347-3354.
[5] Zhang, Zijun., Kusiak, A., et al. (2012) Monitoring wind turbine vibration based on SCADA data. ASME Journal of Solar Energy Engineering, 134:021004.

[6] Dai, Juchuan., Liu, Deshun., et al. (2016) Research on power coefficient of wind turbines based on SCADA data. Renewable Energy, 86:206-215.

[7] Zaher, A., Mcarthur, S., et al. (2009) Online wind turbine fault detection through automated scada data analysis. Wind Energy, 12: 574-593.

[8] Kusiak, A., Li, Wenyan., et al. (2011) The prediction and diagnosis of wind turbine faults. Renewable Energy, 36: 16-23.

[9] Kusiak, A., Verma, A., et al. (2013) Monitoring wind farms with performance curves. IEEE Transactions on Sustainable Energy, 4: 192-199.