Research on the Influence of Wind Characteristics on Output Characteristics of Doubly-fed Wind Turbines

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Abstract. The inherent randomness and intermittence of wind power will make it difficult to accurately predict the output of wind farms and the regulation and stability of power grids. As the output power of the turbine is proportional to the third power of the wind speed, tiny variation of the wind speed will cause much larger fluctuation of the turbine output. With the construction of wind farms gradually moving to non-wind resource-rich areas such as mountainous areas, wind turbines have to face more pulsating wind and greater turbulence intensity. In this paper, based on field measurement data and generated wind conditions, a doubly-fed wind turbine simulation model was built to simulate the influence of different wind condition variations on the output characteristics of the doubly-fed wind turbines. The response of wind turbines to pulsating wind speed is analyzed by using the step response module to simulate the characteristics of wind. By dividing three different working intervals of wind turbine, the influence of different turbulence intensity on the output characteristics of wind turbines is analyzed. The simulation results have theoretical significance for improving the accuracy of wind turbine output prediction and wind turbine optimization design.

1. Introduction
At present, wind farm construction under flat terrain has tended to be saturated. With the construction of wind farms gradually moving to non-wind resource-rich areas such as mountainous areas, wind turbines have to face more pulsating wind and greater turbulence intensity. The randomness and intermittence of wind determine the fluctuation of load and output of wind turbines [1]. This fluctuation of output will bring great difficulties to the optimal control of wind turbines, the overall control of wind farms and the stable operation of power systems [2]. Therefore, it is necessary to analyze the influence of wind characteristics on the output characteristics of wind turbines, and to
establish the operation model of wind turbines, so as to perform the analysis of wind turbines under different operating conditions.

In the past years, Thanks to the great improvement of numerical simulation and observation techniques, considerable progress has been made in solving the problem of parameterization of boundary layer and improvement of DFIG models [3-4]. Wang Jinhang and others analyzed the relationship between wind speed and output torque of wind turbines, and established the grid Voltage-oriented vector control model of doubly-fed wind turbines in PSCAD/EMTDC environment [4]. By introducing hysteresis controller when modelling, Li Bing et al avoids complex coordinate transformation and ensures that the output current frequency remains unchanged when the speed of wind turbine changes [5]. Guo Chunling et al established the model of DFIG on LabVIEW to realize the control of stator voltage and active power. Then analyze the change of stator power when reference value of rotor speed or power stepped [6]. Wei Zheng proposed that the output power variation of wind turbines be used as the judgment basis and control strategy of pitch actuator. According to this strategy, a variable pitch control method based on fuzzy control was further proposed [7]. Based on phase space reconstruction neural network prediction algorithm, Zhang Jinhua set up turbine optimization model aiming at minimizing network loss of wind farm collector system [8]. Üstüntaş T et al introduced cluster center fuzzy logic when estimate turbine power curve [9]. Other scholars compared and validated multiple developed models [10-11].

2. Fundamental theory of wind characteristics

Instantaneous wind speed is composed of average wind speed and pulsating wind speed. The average wind speed calculated at different time intervals is different. According to the theory of time interval determination found by Van Der Hoven at Brookhaven National Labotory [2] Based on the measured results, the average wind speed power spectrum curve as shown in figure 1 is obtained. The figure shows that when the fluctuation period is in the range of 10 minutes to 2 hours, the density of power spectrum curve is low and relatively flat. So the time interval for calculating the average wind speed generally prescribed in the world is 10 minutes. The formula can be expressed as:

$$
\bar{V} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} V(t) dt
$$

![Figure 1. Power Spectrum Curve of Horizontal Wind Speed](image1)

![Figure 2. Generated pulsating wind by Bladed](image2)

The pulsating wind speed is the difference between the instantaneous wind speed and the average wind speed at a certain point in space at a certain time t, Generated pulsating wind is shown in figure 2.
the probability density function of pulsating wind speed is very close to Gauss distribution or normal distribution and can be expressed as follows[2]:

$$P(V') = \frac{1}{\sigma_{V'} \sqrt{2\pi}} \exp \left[ -\frac{V'^2}{2\sigma_{V'}^2} \right]$$

(2)

In the formula, $\sigma_{V'}$ is the root mean square of $V'$.

Turbulence is used to describe the fluctuation degree of the pulsating wind speed variation. And turbulence intensity is defined as the ratio of the standard deviation of the 10 minutes average wind speed to the average wind speed, its mathematical formula is as follows[1]:

$$I = \frac{\sigma}{V}$$

(3)

$I$——Turbulence Intensity; $\sigma$——Standard deviation of mean wind speed

$$\sigma = \left[ \frac{1}{n-1} \sum_{i=1}^{n} (v_i - \bar{v})^2 \right]^{\frac{1}{2}}$$

(4)

Turbulence intensity can be decomposed into three orthogonal components $\sigma_u, \sigma_v, \sigma_w$: longitudinal, transverse and vertical. Normally $\sigma_u > \sigma_v > \sigma_w$, in engineering, the longitudinal turbulence intensity $\sigma_u$ is mainly considered.

The operation characteristics of wind turbines are usually expressed by a cluster of dimensionless performance curves including wind energy utilization coefficient $C_p$ and blade tip speed ratio $\lambda$. $C_p$ is a higher order non-linear function of tip velocity ratio $\lambda$ and pitch angle $\beta$. The following formula is used in theoretical research:

$$C_p(\beta, \lambda) = 0.22 \left( \frac{116}{\lambda} - 0.4\beta - 5 \right)^{-\frac{12.5}{\lambda}} \cdot e^{-\frac{12.5}{\lambda}}$$

(5)

As shown in figure 3, the slight change of pitch angle will cause a significant change in wind power output. The principle is the change of pitch angle will change the attack angle of airflow, which will cause the change of lift-drag ratio and moment of blade. Under the changing wind conditions, the wind turbine can operate in the optimal wind energy absorption state only by adjusting the blade pitch angle and tip speed ratio.

![Figure 3. Performance curve of wind turbine](image-url)
3. Modeling and simulation

In order to analyze the influence of pulsating wind on the output characteristics of doubly-fed wind turbines, a model of doubly-fed wind turbines is built to investigate the transient response of the model to the input of pulsating wind. The output characteristics of wind turbine include dynamic output characteristics and steady-state output characteristics. Dynamic characteristics are the ability of the system to track control signals or suppress disturbances in the dynamic process. The magnitude of steady-state output error reflects the accuracy of model and system control [7].

Figure 4. Model of doubly-fed wind turbine

As can be seen from the figures 4-5, the model is mainly composed of the turbine part and the drive chain part. The turbine will transfer the torque calculated after the considering of pitch angle and power to the drive chain. The model can output 9 parameters such as active power, reactive power, stator voltage and current, pitch angle and so on.

Figure 5. Model of wind turbine and drive chain

In order to verify whether the model can accurately reflect the actual operation of wind turbines, a simulation is carried out under stable wind speed. The wind turbine is set up to run at full capacity, wind speed at the hub is 12 m/s and the simulation time is 2s. The simulation results of the main operation parameters are shown in following figures 6-9:

Figure 6. Steady-state output power  
Figure 7. Steady-state pitch angle response
From the above figures, it can be seen that the main parameters of wind turbine model do not change with time in steady state. Generators operate in super-synchronous state. The above simulation results for the main operating parameters of wind turbine in steady state accord with the steady state characteristics of wind turbine in actual operation in wind farm, which shows that this model of doubly-fed wind turbine can simulate the actual output measurement of wind turbine in steady state very well. It can be used for subsequent dynamic output characteristics analysis.

Set the wind speed at the hub to 12 m/s, when \( t=0.2 \) s, the wind speed changes from 12 m/s to 8 m/s, and the total simulation time is 5 s. The response of main operating parameters of wind turbine model to this condition within 5 seconds is examined. The specific results are shown in the following figure. Because the simulation time is relatively too long, in order to better observe the simulation results of the stator voltage and current when the wind speed steps, 0.8 s to 0.86 s is selected as shown in figures 12 and 13.

**Figure 8.** Steady-state stator voltage

**Figure 9.** Steady-state stator current

**Figure 10.** Wind turbine output power during wind speed stepping

**Figure 11.** Response of pitch angle to wind speed stepping
From the above simulation results, it can be seen that when the wind speed changes from 12 m/s above the rated wind speed to 8 m/s below the rated wind speed, in order to maintain the maximum output of the unit as far as possible, the pitch angle decreases rapidly to 0 degrees to achieve maximum wind energy capture. Because of the inertia of the wind turbine, it has not been reduced below the rated speed in the simulation time, which causes the stator voltage to remain basically unchanged, and the stator current has fallen to a certain extent. Moreover, due to the huge inertia associated with rated operation of wind turbines, the process from oscillation to stability of generator parameters lags behind that of pitch angle. These phenomena are in line with the actual response of wind turbine in wind farm.

Next, based on GH Blade software, the output of doubly fed wind turbines at different wind speeds and turbulence intensities is simulated, and the influence of turbulence intensity on the output characteristics of wind turbines is analyzed. The simulation time is 10 minutes, average wind speed is set at 8 m/s in the transition zone, below rated wind speed, and 14 m/s at full generation respectively. The effects of three turbulence intensities ($I = 0.06; 0.10; 0.14$) on the output power and the speed of doubly-fed generator under two different wind speeds were investigated. Three different turbulence intensities (0.06, 0.10, 014) are set to the wind file during the simulation period of 600 seconds. The Blade software generates random wind conditions of different working intervals as shown in the following figures 14-15. The RMSE of five main parameters are listed in table 1 to visually reflect the effect of turbulence on each output characteristics.

![Stator three-phase voltage during wind speed stepping](image1.png)

**Figure 12.** Stator three-phase voltage during wind speed stepping

![Stator three-phase current during wind speed stepping](image2.png)

**Figure 13.** Stator three-phase current during wind speed stepping
When the average wind speed slightly exceeds the rated wind speed, because of the existence of turbulence, the wind speed at a certain time is not always above the rated wind speed, and the unit does not operate in the ideal rated steady state. The average wind speed is set at 14 m/s. The influence of random wind generated at $I=0.06$, $I=0.10$ and $I=0.14$ on the output parameters of the turbine is shown in the following figures 16-17. The RMSE of five main output characteristics are also listed in table 2.

**Table 1. RMSE in Different Turbulence below rated wind speed**

| parameter | wind speed | active power | electromagnetic torque | mechanical torque | generator speed |
|-----------|------------|--------------|------------------------|-------------------|-----------------|
| $I=0.06$  | 0.425039   | 0.073466     | 289.1511               | 31.39865          | 60.88168        |
| $I=0.10$  | 0.707728   | 0.12436      | 530.0761               | 57.06854          | 87.46871        |
| $I=0.14$  | 0.989454   | 0.174454     | 776.503                | 83.87136          | 120.2054        |

When the average wind speed slightly exceeds the rated wind speed, because of the existence of turbulence, the wind speed at a certain time is not always above the rated wind speed, and the unit does not operate in the ideal rated steady state. The average wind speed is set at 14 m/s. The influence of random wind generated at $I=0.06$, $I=0.10$ and $I=0.14$ on the output parameters of the turbine is shown in the following figures 16-17. The RMSE of five main output characteristics are also listed in table 2.
Table 2. RMSE E in Different Turbulence above rated wind speed

| parameter | wind speed | active power | electromagnetic torque | mechanical torque |
|-----------|------------|--------------|------------------------|-------------------|
| I=0.06    | 0.730558   | 0.018444     | 0                      | 21.21932          |
| I=0.10    | 1.217179   | 0.021514     | 0                      | 24.74842          |
| I=0.14    | 1.703028   | 0.02911      | 75.40746               | 28.20696          |

According to the results of the model, it can be seen that the random wind speed fluctuation with large turbulence intensity has great influence.

4. Conclusions

In this paper, a 1.5MW doubly-fed wind turbine model is established to analyze the influence of fluctuating wind on the output of wind turbines. The parameters of wind turbines under steady-state operation are simulated in accordance with the steady-state output characteristics of wind turbines in actual operation, which proves the accuracy of the model. This model is used to simulate and compare the dynamic output characteristics of wind turbines under different wind speed step conditions, and to analyze the influence of different wind speed step conditions on the output of wind turbines. In addition, the influence of different turbulence intensity on the output parameters of wind turbines in three different working areas is analyzed.

The results show that the output fluctuation of wind turbines operating under large turbulence intensity is obvious, which will bring great difficulty to the safe and stable operation control of wind turbines. With the increase of turbulence, the change of wind speed becomes more and more unpredictable, which makes the control of the turbine more difficult, resulting in uncontrollable fluctuation of the active power output, which brings difficulties to the short-term power prediction accuracy; moreover, the torque of the rotor and transmission shaft fluctuates significantly with the increase of turbulence, which will greatly shorten the life of the gearbox and other components and bring potential safety hazards. This study provides a theoretical reference for the control strategy and structure design of wind turbines in response to complex wind conditions.

Because the accuracy of the model is insufficient at low sampling frequency after verification, the simulation time cannot be too long, which leads to the current failure to study the output fluctuation of wind turbines when the wind speed steps rapidly and continuously. Therefore, it is necessary to continue to optimize the model to improve the simulation accuracy.

This paper only focuses on the direction of a single turbine. In the future, a model in which multiple turbines formulate a wind farm can be studied to simulate multiple cases such as a separated energy and urban context.

References

[1] Ma H Q, Qu N, Li C 2012 Study on Wind Shear Index of Wind Farm Power Grid and Clean Energy 28 88-96
[2] Arslan T, Bulut Y M, Yavuz A A 2014 Comparative study of numerical methods for determining Weibull parameters for wind energy potential Renew. Sustain. Energ. Rev. 40 820-5

[3] Li Y, Liang H H, Wang S D 2012 Diurnal variation of near-surface wind shear based on China Wind Energy Resources Professional Observation Network J. Natural Resources 27 1362-72

[4] Wang J H, Zhao S Z, Wang Z Z, Liu Y L, Gong W J, Li W S 2012 Modeling and Simulation of doubly fed wind turbine under PSCAD/EMTDC environment Renew. Energ. 30 22-6

[5] Li B, Liu S 2018 Maximum Wind Energy Capture Simulation of Brushless Doubly-fed Wind Turbine Comput. Sim. 35 83-7+274

[6] Guo C L, Tian T, Liu Y C 2011 LabVIEW-based simulation of doubly fed wind turbines J. Syst. Sim. 23 331-5

[7] Wei Z, Chen R, Chen J W, Chen J, Gong C Y, Chen Z H 2011 Variable Speed and Variable Pitch Control of Wind Turbine Based on Power Change and Fuzzy Control Chinese J. Electr. Engin. 31 121-6

[8] Zhang J H 2014 Study on optimal unit dispatch in wind farm (Beijing, China: North China Electric Power University)

[9] Üstüntaş T, Şahin A D 2008 Wind turbine power curve estimation based on cluster center fuzzy logic modelling J. Wind Engin. Ind. Aerod. 96 611-20

[10] Mathis W, Hofmann L 2012 Some Aspects of Modelling Wind Turbines and Aggregated Wind Turbines Nonlinear Dynamics of Electronic Systems

[11] Coughlan Y, Smith P, Mullane A et al 2007 Wind Turbine Modelling for Power System Stability Analysis—A System Operator Perspective IEEE T. Power Syst. 22 929-36