Equivalent Modeling of a Direct-Drive Wind Farm Based on the Measured Data

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Abstract. In view of the difference between the wind speed and the actual wind speed in the example, the wind farm with fifteen direct-drive permanent magnet synchronous motors draws the recorded wind speed data on the coordinates of time and wind speed by linear regression to group the change trend. Secondly, the detailed model of wind farm is built in PSCAD, and the multi-machine equivalent model of wind farm is built by the control current source replacing the permanent magnet synchronous motor and the control part. Finally, the simulation analysis shows that the equivalent model reduces the simulation time and accurately reflects the dynamic and transient properties of the wind farm.

1. Introduction
With the continuous improvement of wind power technology level, the grid scale of wind farms is becoming more and more large. The connected operation of large-capacity wind farms will have a great impact on the safe and stable operation of the power grid. The imitation of wind farms is really the basis for studying the power grid operation characteristics after large-scale wind power grid connection.

At present, the dynamic multi-machine equivalent modeling method for direct drive wind farms is mainly divided into the following: Document [3] takes wind speed as the grouping index, but the input wind speed of large wind farms is large to making the number of clusters; Document [4] takes wind speed and three variables reflecting the operating status as the grouping index, the calculation amount is very large for large wind farms. Document [5] uses electromagnetic torque and generator speed as the grouping index, which reduces the calculation amount, but it is not applicable to wind farms with large wind speed fluctuations.

In view of the shortcomings of multi-machine equivalent modeling method, this paper. It can be classified within a large range of wind speed changes, which is more conducive to select wind turbines with better fitted output characteristics.

2. Wind Turbine Set Modeling
The direct-drive permanent magnet synchronous wind turbine set structure includes the following module: turbine, pitch angle control system, permanent magnet synchronous generator, Converter, Converter control system, as shown in Figure 1.
2.1. Turbine Part
The output power of the turbine can be expressed as [7]:

\[ P_m = \frac{1}{2} C_p(\beta, \lambda) \rho \pi R^2 V^3 \]  

(1)

In the formula: \( P_m \) - Wind energy captured by the turbines from the wind; \( V_w \) - wind speed; \( \rho \) - air density, generally 1.225 kg/m\(^3\); \( C_p \) - wind energy utilization coefficient; \( R \) - turbine blade radius; \( \beta \) - blade distance angle; \( \lambda \) - The ratio of turbine tip line speed to wind speed, \( \lambda = (\omega mR) / V \).

\[ \beta = \frac{1}{1 + s T_{\beta}} K_{\beta} (1 + \frac{1}{s T_{1\beta}})(\omega r - \omega_{ref}) \]  

(2)

In the formula; \( \beta \) represents the pitch angle, \( T_{\beta} \) represents the inertia time constant of the pitch angle control system, \( K_{\beta} \), \( T_{1\beta} \) represents the proportion constant of the PI controller in the pitch angle control model, respectively, \( \omega r \) represents the rotor angular velocity, and \( \omega_{ref} \) represents the rated angular velocity.

2.2. Electric Generator
Since a direct drive turbine is used, the connection between the turbine and the generator uses a single block axle model to represent the transmission train [9] of the wind turbine:

\[ \frac{d \omega r}{dt} = \frac{1}{J} (T_e - F \omega r - T_m) \]  

(3)

In formula: \( \omega_r \) is the rotor speed of the generator, and \( \omega_r = \omega_m \), \( T_m \) is the mechanical torque of the turbine output; \( J \) is the rotational inertia of the wind turbine; \( F \) is the torque damping coefficient; \( T_e \) is the electromagnetic torque.

3. Wind Speed Modeling
The rated wind speed was set at 10 m/s. Since there is no turbine input resection control part in the platform, the combination of band-through filter and control switch was used to simulate the turbine cut and resection, with the cut wind speed of 4 m/s and an excision wind speed of 16 m/s. The pitch mechanism adopts the pitch angle control element in the platform, and The ratio of turbine tip line speed to wind speed is 9.68.

Wind speed is random and intermittent, which will affect the wind turbine itself and connected power system. The wind turbine dynamic simulation research requires establish wind speed model. The wind speed \( w(t) \) of the simulated actual effect on the wind turbine is [11]:

\[ u_\lambda(t) = u_{bm}(t) + u_{bg}(t) + u_{xw}(t) + u_{vw}(t) \]  

(4)

In formula: — Basic wind \( u_{bm}(t) \) — Gradient wind \( u_{bg}(t) \) — gust of wind \( u_{xw}(t) \) — Random wind \( u_{vw}(t) \)

Take the fan number 12 as an example, first from the actual wind speed change trend diagram, the basic wind is 9.5 m/s; the gradient wind is the decreasing trend, the running time is 10s, the running time is reduced by 3 m/s. The fold map of the wind speed was segmented fitted to give a
complete gust within the first 5 seconds with a maximum of 2.5 m/s and 1.6 in the latter 5s with a maximum of 2 m/s.

**Table 1.** Values of the random wind parameters

| parameter | Model 1 | Model 2 |
|-----------|---------|---------|
| $K_N$     | 0.004   | 0.004   |
| $F$       | 600     | 200     |
| $\mu$     | 2       | 0       |
| $\Delta \omega$ | 0.5 | 2      |
| $N$       | 100     | 50      |

The simulated wind speed diagram is shown in Figure 2, and the method can simulate the trend of actual wind speed.

![Figure 2. No.12 Actual wind speed and simulated wind speed](image)

4. **Wind Farm Group**

4.1. **Classification Basis**
Draw the scatter plot and then use linear regression to obtain the trend line of wind speed. If the drawn regression curve increases more than 1, the curve can be considered increasing trend. If the drawn regression curve decreases more than 1, the curve can be considered decreasing trend and the other is stable trend. The wind speed mentioned above can be composed of four wind speeds, among which the random wind and gust are accidental, unpredictable, and the basic wind is stable and unchanged, so it can be based on the change trend of the gradual wind, which also supports the wind speed classification mode from the side.

4.2. **Classification Results**
According to the wind speed modeling steps proposed above, the 15 typhoon electric units are 3 units to obtain the grouping results with the wind speed change trend as the grouping index, as shown in Table 2.

**Table 2.** Group results by wind velocity trends

| Number | Group results | trend   |
|--------|---------------|---------|
| 1      | 1-3,11-13,15  | decrease|
| 2      | 6-10          | increase|
| 3      | 4-5,14        | stabilize|

4.3. **Establishment Of The Equivalent Model**

4.3.1. **Characterize the selection of wind turbines** Since the model grid connection method built in this paper is directly connected to the grid, when the load on the wind turbine increases, the power angle will suddenly increase. For the wind turbine with low wind speed, and the lower the wind speed, the more serious the misstep phenomenon is.
The torque angle $\theta_L$ of the steady state when the motor runs meets $0<\theta_L<90$. When the motor is in the torque balance, when the motor load torque increases, the motor slows down the motor due to the electromagnetic torque is less than the load torque, the motor reduces the torque angle $\theta_L$ and the electromagnetic torque to a new stable balance state.

The torque angle $\theta_L$ of the steady-state meets $-90<\theta_L<0$. When the motor load torque increases, the motor slows down, so the motor electromagnetic torque decreases, the motor further deceleration, the actual rotor angle cannot follow the given rotor angle, causing the motor to stall, so the stability area is shown in FIG 3.

![Figure 3. Schematic diagram of the torque balance relationship](image)

The electromagnetic torque equation of the permanent magnet synchronous motor is [12]:

$$T = \frac{mP}{\omega} \left[ \frac{E_d U}{X_d} \sin \theta + \frac{U^2 (X_d - X_q)}{2X_d X_q} \sin 2\theta \right]$$

(5)

In the formula: The $m$ is the phase number of the motor; The $p$ is the number of magnetic poles of the motor; $\omega$ the power angle frequency; the $U$ is the power voltage; $\theta$ the power angle.

For the above formula order $dT/d\theta=0$, then the maximum work angle is:

$$\cos \theta_{max} + \frac{U(X_d - X_q)}{E_0 X_q} (2\cos^2 \theta_{max} - 1) = 0$$

(6)

The solution equation is available

$$\theta_{max} = \cos^{-1} \left( -\frac{1}{4K} \pm \frac{1}{4K} \sqrt{1+8K^2} \right)$$

(7)

In the formula:

$$K = \frac{U(X_d - X_q)}{E_0 X_q}$$

For the same wind farm with different wind speeds, the transient response of the power grid failure during stable operation is not very different. However, the response of wind turbines with different wind speeds when the wind farm is merged into the power grid varies greatly. Therefore, the principle of fan selection should focus on the transient characteristics of the grid-connected moment. The influence of grid connection moment on fan speed is shown in Table 3.

**Table 3. Changes of different wind speed motors immediately connected to the power grid**

| speed/(m/s) | mix/pu | steady/pu | number |
|------------|--------|-----------|--------|
| 10         | 0.925  | 1         | 1      |
| 9.5        | 0.78   | 0.874     | 1      |
| 9          | 0.573  | 0.73      | 2      |
| 8.5        | 0.45   | 0.62      | 5      |
| 8          | 0.39   | 0.5       | 10     |
Finally, the wind power units 6, 14 and 12 are selected as the characterization units, and other wind power units replace the control current source to better meet the operation characteristics and transient characteristics of the wind farm.

4.3.2. Wind turbine equivalent. This paper replaces other except three selected characteristic wind turbine units with control current source, but only equivalent to permanent magnet synchronous motor and converter parts, retaining the turbine part. The current ratio of the control current source to the characteristic fan is:

\[
C = \begin{cases} 
1 & \frac{V_d}{V_b} > \frac{\omega_d}{\omega_b} > \frac{V_n}{\omega_n} \\
1 & \frac{V_d}{V_b} > \frac{\omega_d}{\omega_b} < \frac{V_n}{\omega_n} \\
\frac{P_d}{P_b} & \frac{V_d}{V_b} < \frac{\omega_d}{\omega_b} 
\end{cases}
\]

(8)

In the formula: \(C\) is the proportional coefficient of control current source; \(V_d, V_b, V_n\) represents the equivalent unit wind speed, characteristic unit wind speed and rated wind speed respectively; \(P_d\) indicates the output power unitary of the equivalent unit; \(P_b\) represents the output power unitary of the characteristic unit turbine.

5. Simulation Validation

5.1. Equicollection System of Wind Farm

The collecting system equivalent of the wind farm refers to determining the impedance between the high voltage side of the end transformer of each equivalent wind unit and the low voltage side bus of the main transformer of the wind farm. When \(n\) are similar direct drive wind units in the wind farm, where \(m\) units are divided into one group, equivalent loss method is used to calculate the equivalent resistance.

\[
R_{eq} = \frac{P_{loss}}{3I_{eq}^2}
\]

\[
P_{loss} = \sum_{j=1}^{m} P_{loss_{ij}}, P_{loss_{ij}} = 3\left(\sum_{k=1}^{n} I_k\right)^2 R_{(j, j+1)}
\]

\[
I_{eq} = \sum_{j=1}^{m} I_j, I_j = \frac{\sqrt{P_j^2 + Q_j^2}}{\sqrt{3}U_j}
\]

(9)

In the formula: \(R_{eq}\) is the equivalent resistance of collection system; \(P_{loss}\) is the total active loss of \(m\) unit; \(I_{eq}\) is the output current of equivalent unit; the equivalent resistance calculates the same equivalent resistance, changing the corresponding R to X and P to Q.

5.2. System Simulation

In this paper, 15 direct-drive wind turbines of the same model are selected as calculation examples for modeling and simulation. The rated capacity of the direct-drive permanent magnet synchronous wind turbine is 5 MW, the rated wind speed is 10 m/s, and the stator d and q-axis inductance is 0.28 p.u., the stator resistance is 0.01 p.u. The permanent magnet magnetic chain is 1.04 Wb, and the terminal transformer ratio is 0.69 kV/33 kV, wiring group and the main transformer ratio of Dyn11, wind farm is 33 kV/230 kV. Overhead line connection between the wind turbine and the main substation with resistance of 0.55 * 10^{-2} ohm/km, is 1.265 * 10^{-2} ohm/km.
The simulation time is 10s, the wind power plant is integrated into the power grid at \( t = 0.8s \), the three-phase and single-phase ground short circuit failure at \( t = 6s \), the fault duration is 0.15s. The changes of active power, reactive power and voltage output from the wind farm are shown in Figure 4.

![Figure 4. Changes of active power, reactive power, and voltage](image)

### 6. Conclusion

The simulation results of the detailed model and equivalent model in wind farm and power grid failure show that the change of active power, reactive power and voltage approach under the equivalent trend of wind speed, that is, the modeling method proposed in this paper can accurately reflect the dynamic characteristics of wind farm and outlets, and solve the modeling problem of the value of wind farm under the actual variable wind speed. The detailed model running time is 82 times that of the equivalent model running time, which greatly reduces the simulation time.

However, there are many deficiencies: 1. Failure to analyze the correlation between the same wind speed trends; 2. Failure to properly control the current source will amplify the shock when the system is unstable.3. failed to dig deeper into the wind farm grid.

### 7. Acknowledgments

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