Impact Analysis of Increased Penetration of Variable Speed Constant Frequency Wind Power Generation on Power System Stability

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Abstract. Wind energy has the characteristics of randomness and intermittency. The simulation of the dynamic process on the medium and long-term time scale caused by this is of great significance to the planning and operation of power systems containing wind power. The paper discusses the operating principle of AC-excited variable-speed constant-frequency wind power generation system, analyzes the operating characteristics and control objectives of doubly-fed asynchronous wind generators before and after grid connection, and studies the grid connection of generators based on stator flux-oriented vector control technology Control and tracking control of maximum wind energy. The simulation analysis of the fault disturbance process of the power grid system with variable speed and constant frequency wind turbines, the results verify the correctness of the modeling.

Keywords: impact analysis, variable speed constant frequency wind power generation, power system stability.

1. Introduction
As the proportion of wind power in the power system continues to increase, its impact on the power system can no longer be ignored. Because the working principle and connection method of wind turbines are quite different from traditional three-phase synchronous generators, the accurate modeling of wind turbines is to analyse the impact of large-scale wind power connection on the stability, safety, and reliability of the grid and other key steps. On the other hand, the continuous advancement of power electronics technology has prompted variable-speed and constant-frequency units to gradually replace constant-speed and constant-frequency units as the main model of grid-connected wind turbines. While improving the controllability of wind power systems, variable-speed and constant-frequency units have also increased to increase its complexity. Due to the introduction of a large number of power electronic switches, the dynamic process of a variable-speed constant-frequency unit cannot be represented by a continuous equation [1]. In addition, the wind power generation system is coupled with various physical systems such as aerodynamic system, mechanical system, electrical system, control and protection system, etc. Dynamic, so it is very difficult to use analytical methods to study its dynamic characteristics, so it is necessary to use simulation methods to study it. Based on the characteristics of wind power generation, the author emphatically analyzes the characteristics,
classification and operating principles of doubly-fed induction variable-speed constant-frequency wind turbines; on the basis of researching the characteristics of each component of variable-speed constant-frequency wind turbines, it summarizes the domestic Scholars on the current research status of DFIG wind turbine model, discussed the modeling of the system under different operating conditions.

2. Classification and principles of wind turbines

2.1. Constant speed and constant frequency wind turbine

Constant-speed and constant-frequency wind turbines operate near the rated speed, and the slip variation range is small, so the generator output frequency changes are also small, so it is called a constant-speed and constant-frequency wind turbine, as shown in Figure 1.

![Figure 1. Constant speed and constant frequency wind turbine](image)

Constant-speed and constant-frequency fans include two types of constant pitch and variable pitch. It mainly uses the stall characteristics of the blade shape, that is, when the wind speed is higher than the rated wind speed, after the stall condition is reached, the surface of the blade generates vortex, and the efficiency is reduced. So as to achieve the purpose of limiting power [2]. The advantages of fixed pitch models are simple adjustment and control, but the disadvantage is that the main components such as blades, hubs, towers, etc. are increased in force, and the output of the wind turbine decreases when the wind exceeds the rated wind speed. When the wind speed is higher than the rated wind speed, the variable pitch fan reduces the absorbed wind energy by adjusting the pitch angle, so that the active power output by the wind turbine remains stable.

2.2. Working principle

The conversion of wind energy into mechanical energy by the blades of a wind turbine is a complex process involving aerodynamics and fluid mechanics. In the research of power systems, A simplified modeling method is usually used to describe the relationship between wind speed $v_a (m/s)$ and mechanical power $P_a (W)$ captured by the wind turbine:

$$P_a = \frac{1}{2} \rho \pi R^2 v_a^3 C_p (\theta, \lambda)$$

(1)
Where $\rho$ is the air density, $\text{kg/m}^3$; $R$ is the radius of the wind wheel, m; $\lambda = \omega_{t}R/v_{w}$ is the tip speed ratio; $\omega_{t}$ is the wind turbine speed; $\theta$ is the pitch angle, deg; $C_{p}$ is the wind energy conversion efficiency coefficient of the wind turbine, which is $\lambda$. The function of $\lambda$ and $\theta$ is shown in Figure 2.

![Figure 2. The relationship curve between fan efficiency and blade tip speed ratio and pitch angle](image)

Based on the full power converter, the electrical part and the mechanical part of the wind turbine are completely decoupled. The DFIG can also achieve the decoupling of the electrical and mechanical parts under normal operation. Therefore, the wind turbine can adopt the elementary mass model in the steady state [3]. However, when studying the transient response of the wind turbine, if the oscillation of the shaft system is to be studied, at least a two-mass model is required. Generally, the wind turbine rotor can be equivalent to a mass block with a larger inertia $H_{t}$, and the gearbox (if any) and the generator rotor can be equivalent to a mass block with a smaller inertia $H_{s}$. The two-mass shaft system of the wind turbine the mathematical model is (standard unit system)

$$
\begin{align*}
2H_{t}P\omega_{s} &= T_{r} - K\delta - D_{s}\omega_{s} \\
2H_{s}P\omega_{s} &= K\delta - T_{r} - D_{s}\omega_{s} \\
\rho\delta &= \omega_{o} (\omega_{r} - \omega_{o})
\end{align*}
$$

(2)

Where $P$ is the differential operator $d/dt$; $K$ is the stiffness coefficient of the shafting system, $(\text{kg} \cdot \text{m}^2) / \text{s}^2$; $\delta$ is the relative angle between the two masses, rad; $\omega_{o}$ is the synchronous speed (314.16rad/s in a 50Hz system); $\omega_{r}$ and $\omega_{s}$ are respectively Is the rotor speed of the wind turbine and generator; $T_{r}$, $T_{e}$ is the mechanical torque of the wind turbine and the electromagnetic torque of the generator respectively [4]. When the shaft stiffness coefficient $K$ tends to infinity, the speed at both ends of the shaft system is the same, and the relative angle is 0, that is, the shaft system is simplified to a single-mass model. If it is necessary to study the dynamic process or subsynchronous oscillation of the fan shaft system itself, a more detailed multi-mass shaft system model can be used.
In the electromechanical transient analysis, the main concern is the control characteristics of the PWM converter, so the average model is used. Assuming that the PWM modulated wave is an ideal modulated wave (infinite frequency), and the parallel resistance in the DC link represents the loss, the PWM converter model can be expressed as:

\[
\begin{align*}
U_{ac} &= \frac{\sqrt{3}}{2\sqrt{2}} m U_{dc} \\
U_{dc} I_{dc} + \sqrt{3} \text{Re}(U_{ac} I_{ac}) &= 0
\end{align*}
\] (3)

In the formula: \(U_{ac}\) and \(I_{ac}\) are the AC line voltage phasor and line current phasor respectively; \(U_{dc}\) and \(I_{dc}\) are the DC voltage and current respectively; \(m\) is the modulation ratio (0 < \(m\) < 1). Due to the fast response speed of the current control loop, its dynamics can be ignored when the simulation step is large, that is, the AC side current of the PWM converter is always equal to its reference value. At this time, from the AC side, the PWM converter can be equivalent to a three-phase controlled current source.

3. Simulation analysis

The DFIG used in this experiment is an ordinary wound asynchronous motor, not a specially designed generator. If the rotor is in enhanced excitation and power generation operation, the rotor magnetic circuit will be saturated, causing rotor current distortion, and the stator voltage will be distorted through electromagnetic coupling [5]. The solution to this problem is to add a 200V/380V step-up transformer between the DFIG grid to equivalently reduce the stator terminal voltage and the saturation of the corresponding magnetic circuit. In the experiment, the initial angle of the rotor is determined by applying DC voltage to the stator AB and rotor ab phases. At this time, the stator and the rotor are equivalent to two magnets and will be fixed in the same position. Use a photoelectric encoder to record this position, which can be used as the starting angle of the rotor.

When the motor speed is increased before grid connection, the stator voltage increases slightly, but this situation does not have a big impact on grid connection. In order to accurately match the stator voltage with the grid voltage before grid connection, the voltage can be increased outside the rotor current inner loop Negative feedback suppresses the rise of the stator voltage and enables the system to achieve flexible grid connection in a wider range. The reason for this phenomenon is that the \(L_m\) parameter used in the control model is a static parameter, and its dynamic parameter identification needs further study.

3.1. Wind power output under wind speed disturbance

It can be seen from Figure 3 that when the system is disturbed by wind speed, the output active power of the wind farm changes. Because the QSS model ignores part of the rapid change process, such as some links in the control system with small time constants, and the QSS simulation step has a large value, the QSS curve is smoother and has a slight deviation from the FTS curve. However, the overall change trend of the two is the same, so it will not affect the dynamic performance analysis on the medium and long-term time scale [6]. In the simulation, the time spent in the calculation using the QSS method is greatly reduced, which significantly improves the simulation efficiency. It can be seen that the QSS model established in this paper is effective and can be used to study the dynamic process of wind turbine grid-connected wind speed disturbance.
3.2. Grid-connected process simulation

The generator is connected to the grid after running at a speed of 1200r/min under no-load and steady state for 3s. The no-load adjustment process, effect and the waveform of the rotor current transition process at the moment of grid connection are shown in Figure 4. It can be seen that $U_{dc}$ quickly follows $\dot{U}_{ac}$ in the figure, and $I_{dc}$ is also very stable and almost zero, which is consistent with the aforementioned control strategy; the error between the stator a-phase output voltage $D$ and the grid a-phase voltage $U_{UUNet}$ is within half a cycle. The internal value is below 10V, indicating that the adjustment process is faster and the accuracy is higher; the rotor a-phase current air does not have much impact, the transition is relatively stable, and it will not cause much impact on the grid, and it fully meets the grid connection requirements.

\[
\begin{align*}
|\dot{U}_{ac}| &= \frac{\sqrt{3}}{2\sqrt{2}} m U_{dc} \\
U_{dc} I_{dc} + \sqrt{3} \text{Re}(\dot{U}_{ac} I_{ac}) &= 0
\end{align*}
\]
3.3. Simulation of active power regulation process
After connecting to the grid, the wind speed is set at 6.5m/s, the wind speed is changed from 6.5m/s to 7m/s at 8.5s, and then back to 6.5m/s at 12.5s, and the simulation ends at 16.5s. During the simulation, set the reactive power to 600var unchanged [7]. The simulation result is shown in Figure 5, only changing the set wind speed, when the wind speed changes from 6.5m/s to 7m/s, the active power P will increase, and the actual values of the active and reactive power are well tracked In the corresponding change of the MT component of the rotor current, only the absolute value of the active component increases, while the reactive component remains unchanged, indicating that the active power can be adjusted independently, and it can be seen that the two components of the rotor current are also very good Tracking the given change; when the given wind speed changes from 6.5m/s to 7m/s, the motor speed changes from the best speed corresponding to 6.5m/s wind speed to 1300r/min to the best speed corresponding to 7m/s wind speed The best speed is 1400r/min. When the given wind speed changes from 7m/s back to 6.5m/s, the motor speed also changes from 1400r/min back to the best speed 1300r/min corresponding to the wind speed of 6.5m/s. It shows that during the change of wind speed, the unit operates according to the mechanism of maximum wind energy capture.

4. Conclusion
In this paper, field-oriented vector control technology is used to study the grid-connected control and maximum wind energy tracking control of AEVSCF wind turbines. Then, the no-load model and power generation model of the generator are established through separate modeling and time-sharing simulation methods. It constitutes an AC-excited variable-speed constant-frequency wind power simulation system. Simulation research on grid-connected control and maximum wind energy tracking control of AC-excited variable-speed constant-frequency wind turbines shows that the grid-connection process of the generators is stable and the current impact is small; after grid-connection, the generators can reliably operate on the basis of variable-speed constant-frequency Tracking changes in wind conditions and maximizing the conversion of wind energy into electrical energy can significantly improve the operating efficiency of the unit.
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