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Research on power coefficient of wind turbines based on SCADA data

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ABSTRACT

Power coefficient C_p is an important parameter for wind turbine design and operational control. Wind speed is the basic calculation parameter of the power coefficient. Since the anemometer is fixed on the nacelle, the measured wind speed is different from the wind speed in front of the wind rotor. Calculation error will produced if the directly measured wind speed is used to calculate the power coefficient. In this paper, a calculation model of the wind speed in front of the wind rotor is presented based on the SCADA data and the aerodynamic theory. Two power coefficient calculation methods are proposed. One is based on the statistical data and the other is based on the real-time data. An actual calculation result for a 2 MW wind turbine shows that the power coefficient is near or greater than 0.593 (the theoretical maximum value) if the directly measured wind speed is used during the maximum power point tracking (MPPT). After wind speed correction, the power coefficient is reduced to 0.397 that is more realistic. When using the real time data, the power coefficient is time-varying even in the region of MPPT, since wind speed is time-varying and the wind rotor rotational speed regulation is delayed due to the wind rotor moment of inertia.

1. Introduction

Wind turbines can convert the kinetic energy in the wind into electrical energy. The capture efficiency of wind energy is the most basic index which is also called the power coefficient [1]. In the process of theoretical design, the power coefficient can be calculated using the theory of aerodynamics, such as the blade element momentum (BEM) theory [1,2], generalized dynamic wake (GDW) theory [3] and computational fluid dynamics (CFD) method [4]. In many literatures, extensive researches have been carried out to improve the power coefficient of wind turbines. For delivering maximum electric power, neural network principles [5], fuzzy logic [6], and neuro-fuzzy inference system (ANFIS) [7] are used for wind speed estimation and maximum wind power extraction. Unlike the conventional maximum power point (MPPT) tracking methods employing a lookup table, a method based on a linear relationship between V_{dc}^2 and I_{dc} is used to carry out MPPT [8]. Based on the measurement values of voltage and current at rectifier terminals in wind turbines, rotor speed control algorithm is established to maintain the maximum value of the power coefficient even considering the inertia effect [9]. Employing a step-up DC–DC converter, a simple control method for MPPT tracking in a variable speed wind turbine is presented, which has good flexibility, and low cost [10].

The above mentioned researches mainly consider the control methods of the power coefficient. However, in the actual wind farm, the effective measurement of the power coefficient is difficult. If air density, humidity, temperature, wind speed and tip speed of the blade are obtained, the power coefficient curve can be identified [11]. Since the anemometer is fixed on the nacelle, wind speed obtained from it is different from the actual wind speed due to blade rotating. If the measured wind speed is used to calculate the power coefficient, error will occur. In literatures [12,13], considering the mechanical power of the wind turbine rotor can be represented using a nonlinear function of wind speed, shaft speed and pitch angle, wind speed is estimated using Gaussian radial basis function network and then used to be the optimal power reference. This method needs to know the relationship between the mechanical power and wind speed, so it isn't suitable to carry out the wind speed correction. The more usual approach is to add an experience value to the measured wind speed but lacking theoretical basis.

In this paper, a novel idea is presented to calculate the power coefficient which makes the best use of SCADA data coming from a

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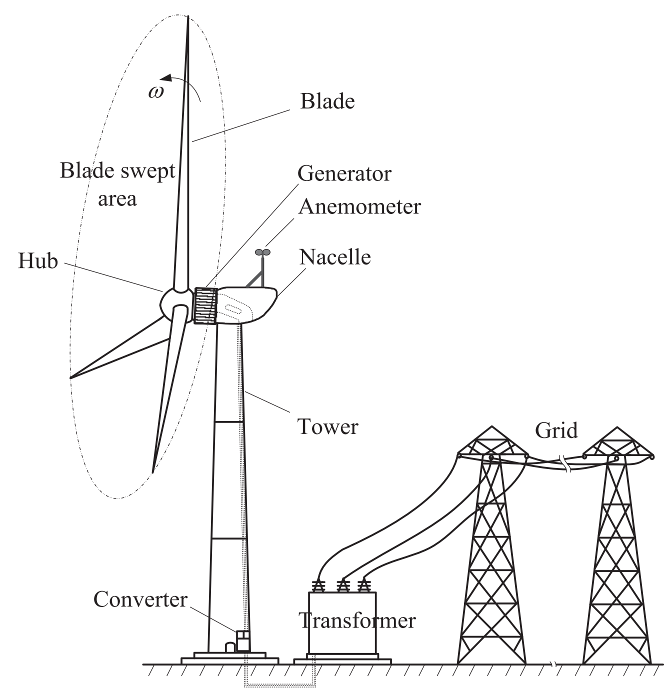
direct drive wind turbine. SCADA (supervisory control and data acquisition) system has been equipped in large scale wind turbines widely. Many running parameters including wind speed, rotational speed of the wind rotor, and generator power can be obtained from it [14]. Using these data and combing with the aerodynamic theory, two power coefficient calculation methods are proposed. It can be used to evaluate the wind turbine performance in actual wind farm, offer design and control references.

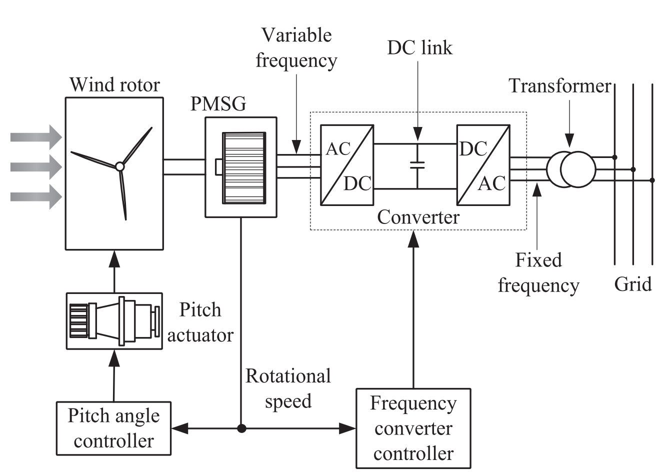
2. Structure of wind turbines and its SCADA system

2.1. Structure of wind turbines

Fig. 1 shows a typical structure of direct drive wind turbines. Fig. 1(a) shows the apparent structure that consists of the blade, hub, generator, converter, nacelle, tower and some other parts. Fig. 1(b) shows the functional structure including the wind rotor, PMSG, converter, transformer, controller, etc. The function of the wind turbine blade is to capture wind energy and convert it into mechanical energy. The function of the hub is to fix blades which rotate with the generator rotor synchronously. Unlike doubly-fed induction wind turbines, direct drive wind turbines have no intermediate gear box and the hub is directly connected with the generator rotor. The function of the generator is to convert the mechanical energy into electrical energy. Its main form is multi pole permanent magnet synchronous generator (PMSG). Since wind speed is time-varying, the rotational speed of the generator rotor is also time-varying which means the output AC frequency of the generator is unstable. So it is necessary to connect the generator and the power grid through a full-scale frequency converter system. It can control the rotational speed of the generator rotor and the power flow to the power grid. As illustrated in Fig. 1(b), the full-scale frequency converter consists of two voltage source converters in the form of back-to-back. Through the DC link, the generator-side converter and the grid-side converter are connected. In the generator-side converter, the electric frequency is adjustable according to the optimized mechanical frequency; its voltage is on a desired level [15]. In the grid-side converter, the electric frequency is fixed being equal to the grid frequency. The nacelle is used to fix the generator, mounted on the tower top. It is also used to fix the anemometer. The tower is the support structure of wind turbines, fixed on the ground. The converter is usually placed in the bottom of the tower. Table 1 shows some parameters of 2 MW wind turbines used for field tests.



(a) Apparent structure of direct drive wind turbines



(b) Functional structure of direct drive wind turbines

Fig. 1. Structure of direct drive wind turbines.

2.2. SCADA system of wind turbines

The wind turbine SCADA system is a data acquisition, monitoring and control system based on computer technology, communication technology, control technology and sensor technology (3C + S). Using the SCADA system, the operational state parameters of wind turbines can be obtained including wind speed, wind direction, rotational speed of the wind rotor, pitch angle, generator power and so on. Based on the SCADA data, many researches have been carried out, such as fault identification [14], vibration analysis [16,17]. Since the amount of data is rather large, state parameters are sampled per second (sampling frequency: 1 Hz) and stored in the server. The data process software in the following sections is MATLB. The SCADA data pattern is shown in Table 2 which is coming from Chenzhou Lu Hejin wind farm in China.

3. Power coefficient

According to the aerodynamic theory, when air mass is flowing through an area S with speed v, the power of the air movement is expressed as [18].

$$P_{\text{wind}} = \rho v^3 S/2 \tag{1}$$

where, ρ is the air density which decreases with increasing altitude

Table 1
2 MW wind turbine parameters.

Parameters	Value	Parameters	Value
Rated power (kW)	2000	Cut-in wind speed (m/s)	3
Wind rotor diameter (m)	95.9	Rated wind speed (m/s)	11
Tower height (m)	80	Cut-out wind speed (m/s)	22
Blade numbers	3	Maximum wind speed (m/s)	70
Blade length (m)	46.5	Rated rotational speed (r/min)	6–17