Fundamentals of Renewable Energy: Wind

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Abstract— Energy is essential to everyone's life no matter when and where they are. This is especially true in this new century, where people keep pursuing higher quality of life. Among different types of energy, electric energy is one of the most important that people need every day. In this paper we have a review on the fundamental of Wind Energy.

Keywords—Renewable energy-Wind Energy.

I. INTRODUCTION

Due to ever increasing energy consumption, rising public awareness of environmental protection, and steady progress in power deregulation, alternative (i.e., renewable and fuel cell based) distributed generation (DG) systems have attracted increased interest wind and photovoltaic (PV) power generation are two of the most promising renewable energy technologies. Fuel cell (FC) systems also show great potential in DG applications of the future due to their fast technology development and many merits they have, such as high efficiency, zero or low emission (of pollutant gases) and flexible modular structure.

II. WHY ALTERNATIVE ENERGY?

The term “alternative energy” is referred to the energy produced in an environmentally friendly way (different from conventional means, i.e., through fossil-fuel power plants, nuclear power plants and hydropower plants). Alternative energy considered in this dissertation is either renewable or with high energy conversion efficiency. There is a broad range of energy sources that can be classified as alternative energy such as solar, wind, hydrogen (fuel cell), biomass, and geothermal energy. Renewable energy resources are not only renewable, but also abundant: For example, according to the data of 2000, the U.S. wind resources can produce more electricity than the entire nation would use [1]. The total solar energy from sun in a day at the earth surface is about 1000 times more than the all fossil fuels consumption.

III. WIND ENERGY

Wind energy is one of world's fastest-growing energy technologies. Both the global and U.S. wind energy experienced a record year in 2005. According to the figures released by the Global Wind Energy Council (GWEC), in 2005 there was a 43.4% increase in annual additions to the global market and a 564.2% increase in the annual addition to the U.S. wind power generation capacity. Last year was just one of the record years. In the past 11 years, the global wind energy capacity has increased more than 17 times — from 3.5 GW in 1994 to almost 60 GW by the end of 2005 (Figure 1). In the United States, wind power capacity has increased more than 3 times in only 5 years (from 2554 MW in 2000 to 9149 MW by the end of 2005), also shown in Figure 1. The future prospects of the global wind industry are also very promising even based on a conservative projection that the total global wind power installed could reach 160 GW by 2012. A spread of new countries across the world will participate in the global wind energy market in the next ten years [2].

The phenomenal worldwide growth of the wind industry during the past decade can be attributed to supportive government policies and the fast development in innovative cost-reducing technologies. In the U.S., the work conducted under the Wind Energy Program’s Next Generation Wind Turbine (1994 – 2003) and WindPACT (1999 – 2004) projects under the Department of Energy (DOE) resulted in innovative designs, high power ratings, and increased efficiencies [3]. All these technological advances have led to
dramatic reductions in cost of electricity (COE) from $0.8/kWh in the early 1980s to about $0.04/kWh today for utility-scale (normally >= 750kW) turbines [3], [4]. Although this drop in COE has been impressive, more research work is still needed to make wind power more competitive. Development in aerodynamic efficiency, tructural strength of wind turbine blades, larger turbine blades and higher towers, variable speed generators, and power controllers will help to reduce the COE further. The DOE goal is to reduce the COE produced by land-based utility-scale turbines located in Class 4 wind resource areas (areas with 5.8 m/s wind speed at a 10-m height) to $0.03/kWh by 2012 [3].

IV. ENERGY IN WIND

Wind energy systems harness the kinetic energy of wind and convert it into electrical energy or use it to do other work, such as pump water, grind grains, etc. The kinetic energy of air of mass m moving at speed v can be expressed as

\[ E_k = \frac{1}{2}mv^2 \]  

(1)

During a time period t, the mass (m) of air passing through a given area A at speed v is:

\[ m = \frac{\rho Avt}{2} \]  

(2)

where \( \rho \) is the density of air (kg/m3).

Based on the above two equations, the wind power is

\[ P = \frac{1}{2} \rho A v^3 \]  

(3)

The specific power or power density of a wind site is given as

\[ P_{den} = \frac{P}{A} = \frac{1}{2} \rho v^3 \]  

(4)

It is noted that the specific power of a wind site is proportional to the cube of the wind speed.

V. POWER EXTRACTED FROM WIND

The actual power extracted by the rotor blades from wind is the difference between the upstream and the downstream wind powers

\[ P = \frac{1}{2} km (v^2 - v_0^2) \]  

(5)

where \( v \) is the upstream wind velocity at the entrance of the rotor blades, \( v_0 \) is the downstream wind velocity at the exit of the rotor blades, \( km \) is the mass flow rate, which can be expressed as

\[ km = \rho A \left( \frac{v + v_0}{2} \right) \]  

(6)

where \( A \) is the area swept by the rotor blades.

From (5) and (6), the mechanical power extracted by the rotor is given by:

\[ P = \frac{1}{2} \rho A \left( \frac{v + v_0}{2} \right) \left( v^2 - v_0^2 \right) \]  

(7)

Let \( C_{p} = \frac{1}{2} \left( 1 + \frac{v}{v_0} \right) \left[ 1 - \left( 1 - \frac{v_0}{v} \right)^2 \right] \cdot \]

\[ P = \frac{1}{2} \rho A v^3 C_p \]  

(8)

\( C_p \) is called the power coefficient of the rotor or the rotor efficiency. It is the fraction of the upstream wind power, which is captured by the rotor blades and has a theoretical maximum value of 0.59, shown in Figure 2. In practical designs, maximum achievable \( C_p \) is between 0.4 and 0.5 for high-speed, two-blade turbines and between 0.2 and 0.4 for low-speed turbines with more blades [1].

It is noted from (8) that the output power of a turbine is determined by the effective area of the rotor blades (A), wind speed (v), and wind flow conditions at the rotor (Cp). Thus, the output power of the turbine can be varied by changing the effective area and/or by changing the flow conditions at the rotor system. Control of these quantities...
forms the basis of control of wind energy systems.

VI. TIP SPEED RATIO

The tip speed ratio $\lambda$ (TSR), defined as the ratio of the linear speed at the tip of the blade to the free stream wind speed, is given as follows [1]:

$$\lambda = \frac{\omega R}{v}$$  \hspace{1cm} (9)

where $R$ is the rotor blade radius and $\omega$ is the rotor angular speed.

TSR is related to the wind turbine operating point for extracting maximum power. The maximum rotor efficiency $C_p$ is achieved at a particular TSR, which is specific to the aerodynamic design of a given wind turbine. For variable TSR turbines, the rotor speed will change as wind speed changes to keep TSR at some optimum level. Variable TSR turbines can produce more power than fixed TSR turbines [5].

VII. WIND ENERGY CONVERSION SYSTEM

The block diagram of a typical wind energy conversion system is shown in Figure 3.

![Figure 2. Theoretical rotor efficiency vs. $v_0/v$ ratio.](image)

![Figure 3. Block diagram of a typical wind energy conversion system.](image)
VIII. CONSTANT SPEED VARIABLE SPEED WIND ENERGY
CONVERSION SYSTEMS (WECS)

Generally, there are two types of wind energy conversion
systems: constant speed and variable speed systems, shown
in Figure 4 [5]. In Figure 4 (a), the generator normally is a
squirrel cage induction generator which is connected to a
utility grid or load directly. Since the generator is directly
coupled, the wind turbine rotates at a constant speed governed
by the frequency of the utility grid (50 or 60 Hz) and the
number of poles of the generator. The other two wind power
generation systems, shown in Figure 4 (b) and (c), are variable
speed systems. In Figure 4 (b), the generator is a doubly-fed
induction generator (wound rotor). The rotor of the generator
is fed by a back-to-back converter voltage source converter.
The stator of the generator is directly connected to load or
grid. Through proper control on the converter for the rotor, the
mechanical speed of the rotor can be variable while the
frequency of output AC from the stator can be kept constant.
Figure 4 (c) shows a variable speed system which is
completely decoupled from load or grid through a power
electronic interfacing circuit. The generator can either be a
synchronous generator (with excitation winding or
permanent magnet), or an induction generator. In this
dissertation, a variable speed WECS, similar to the one shown
in Figure 4 (c), is used for the hybrid energy system study. The
generator used in the study is a self-excited induction
generator.

IX. WIND TURBINES OUTPUT POWER VS. WIND SPEED

A typical power vs. wind speed curve is shown in Figure 5 [5],
[6]. When the wind speed is less than the cut-in speed
(normally 3-5 m/s) [5], there is no power output. Between the
cut-in speed and the rated or nominal wind speed (normally
11-16 m/s) [5], the wind turbine output power is directly
related to the cubic of wind speed as given in (2.51). When the
wind speed is over the nominal value, the output power needs
to be limited to a certain value so that the generator and the
corresponding power electronic devices (if any) will not be
damaged. In other words, when the wind speed is greater than
the rated value, the power coefficient Cp needs to be reduced
[see (8)]. When the wind speed is higher than the cut-out speed
(normally 17-30 m/s) [5], the system will be taken out of
operation for protection of its components.

There are several ways to control the wind turbine output
power. The two common ways to achieve this goal are: stall
control and pitch control.[1]-[6]

It is noted from figure 5 that a variable speed system normally
has lower cut-in speed. The rated speed is also normally lower
than a constant speed system. For wind speeds between the cut-in and the nominal speed, there will be 20-30% increase in the energy capture with variable speed compared to the fixed-speed operation[1]-[6], shown in Figure 5. For a pitch controlled wind system, the power for wind speeds over the nominal value can be held constant precisely. On the other hand, for a stall controlled constant speed system, the output power will reach its peak value somewhat higher than its rated value and then decreases as wind speed grows.

REFERENCES