41.3 Wind Turbines

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Introduction

Historical Sketch

The development of windmills has a long tradition. Windmills were already in use in Japan and China thousands of years ago. The great irrigation systems of Babylon are thought to have been powered by windmotors. Examples of windmills erected almost 2000 years ago still exist in Egypt.

Wind power generation was first introduced to the Western world around the 8th century A.D. By the 16th century windmills were a significant source of energy in Great Britain, Holland, and Germany. As late as 1900, the entire wheat crop of Northern Europe was ground by windmills scattered across Holland, Denmark, and Germany.

Although windmills played an essential role in the development of the Netherlands, only about 1000 windmills are still in existence, compared to an estimated 10,000 units at the turn of the century. Although considerable research effort has been expended to improve the aerodynamic efficiency of the classic Dutch design, little improvement can be made without altering its unique aesthetics.

Windmills have also played a significant role in the development of rural areas in many parts of the world including the United States. It has been estimated that 6.5 million units were built in the U.S. from 1880 to 1930. Most were used for pumping water and running sawmills, but some were used to meet the relatively light electrical needs for a farm household. It is still possible for a small windmill to supply the electrical needs of an American family.

Until recently, most windmills have been used as a direct and localized source of energy. Since the energy crisis in the 1970s the emphasis has shifted toward developing wind generation systems that are suitable for integration into the power grid. The first windmill designed to exceed 1 MW in capacity was erected in the U.S. in 1941. Conceived by P. C. Putnam, it was a two-blade design having variable pitch with a diameter of 53 m (175 ft) and mounted on a 34 m (110 ft) tower on Grandpa's Knob near Rutland, VT. Designed to produce 1.2 MW at 14 m/s (30 mph), its average power delivery to the AC power grid of the Central Vermont Public Service Corporation was only 210 kW at an average wind velocity of 8 m/s, far below the estimated average wind velocity of 11 m/s. Although its power production was below expectations, it operated successfully from 1941 to 1945 with reasonable reliability in winds as high as 31 m/s and was able to withstand the loading of 51 m/s (115 mph) winds. Fatigue-induced failure of the stainless steel blades terminated its operation. Technical feasibility was proven but, at that time, relatively abundant sources of hydroelectric energy were more economical. Larger windmills were not developed until 30 years later. Current research has focused on electric generation, incorporating sophisticated aerodynamics technology.

Windpower Potential

Estimates of wind energy potential vary widely because of the lack of adequate data and the high variability of wind speed both temporally and spatially. It is thought that about 2.5% of the power radiated to earth from the sun is contained in atmospheric motion. This amounts to a total power level of about 2×10^9 MW. Of this, an estimated 2×10^7 MW is available from selected sites around the world.

Within the U.S., wind power capacity has been projected by the U.S. Department of Energy to be between 120,000 and 200,000 MW by the year 2030. The realization of this potential is strongly dependent on public policy. The wind power potential in the state of California has been realistically estimated to be 7000 MW at prime locations. By 1992 approximately 1700 MW had been developed because of very favorable tax credits. Because of the wide variability in wind speed, it is difficult to quantify the annual energy that can be produced with this capacity. The potential electrical output in kWh/kW for a turbine rated at 11.2 m/s (25 mph) can range from less than 750 h to more than 5000 h, depending on location in the world [Warne and Calhan, 1977]. Experience has also shown that the decrease in wind velocity within an array of turbines can be underestimated. This has been an acute problem in areas where extensive wind power development occurs.

Wind Turbine Aerodynamics

There are two fundamental types of turbines. The horizontal-axis wind turbines (HAWT) are efficient but have structural problems and require a special yaw drive mechanism to maintain alignment with the prevailing wind. Vertical-axis wind turbines (VAWT) have simplified gearing and strength requirements, but are not as efficient as HAWTs. The theory of HAWTs is more developed and will be outlined here. The theory of VAWTs is discussed in Spera [1994].

Wind power is calculated on the basis of total kinetic energy per unity time passing through a unity cross-sectional area normal to the flow:

$$\frac{P}{A}=\frac{1}{2}\rho V^3 \tag{41.52}$$

where ρ is the air density and V the wind speed. The performance of a wind turbine can be expressed as a power coefficient:

$$C_p \equiv \frac{P}{\frac{1}{2}\rho V^3 A} \tag{41.53}$$

The basic aerodynamics of a windmill are the same as a propeller in reverse. Aerodynamic forces are induced on each blade element whose magnitude and direction are dependent on wind velocity, V, the rotational speed, Ω, and the blade pitch angle, β. There is a component of the lift force acting in the direction of rotation that produces a torque and hence power. The **actuator disk** theory can be used to calculate ideal power given by [Betz and Prandtl, 1919]

$$C_p = 4(1-a)^2 a \tag{41.54}$$

where a is a factor accounting for the deceleration of wind through the windmill rotor as shown schematically in Fig. 41.33. Maximum power is attained when a is 1/3. Thus, the ideal power of a windmill is $C_p = 16/27 = 0.593$.*

Even under ideal conditions only a little more than one-half of the available wind power per unit area can be extracted by a windmill. More detailed analysis, which includes the effects of rotation in the slip stream, shows that the ideal power developed depends on the relative rotational speed or **specific speed**, $\Omega R/V$ [Glauert, 1935]. This is illustrated in Fig. 41.34, which shows that a theoretical power factor of 0.593 is only approached when the tip speed of a windmill exceeds about four times the wind speed. In addition, maximum aerodynamic performance of a blade section is attained when the angle of attack to the relative wind is a specified value depending on the blade section shape. In order for this criterion to be compatible with the ideal power at a given relative tip speed, the blade area expressed as a percentage of **disk area** must decrease with an increase in design speed. Theoretical values of the product of solidity, defined as

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* This can be misleading since the flow through the rotor is ρ A V (1 – a), not ρ A V. Maximum rotor efficiency, defined as power output/power input, occurs at a = 0.5 when the wind velocity in the far wake, (V – 2a), is equal to zero.

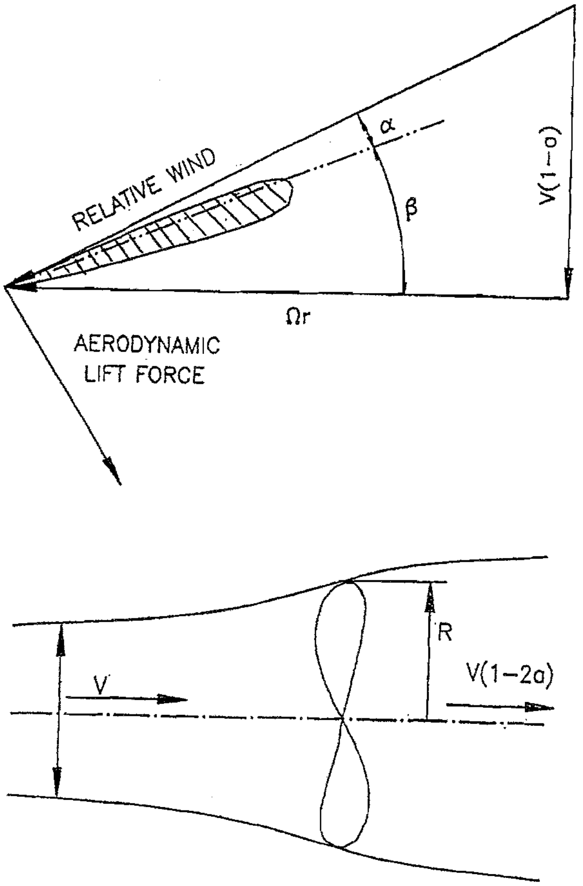

FIGURE 41.33 Schematic of flow through a windmill rotor.

$$\sigma \equiv \frac{\text{blade area}}{\pi R^2} \tag{41.55}$$

and design lift coefficient, C_L, are as shown in the table below.

Theoretical Solidity as a Function of Specific Speed

$\Omega R/V =$	1	2	3	4	5
$\sigma C_L =$	0.98	0.48	0.29	0.19	0.14

Thus, if the design lift coefficient is 1.0, the theoretical blade area would be around 100% of the area swept by the blades for a slow running windmill ($\Omega R/V = 1$) and only 14% of the disk area for a relatively high-speed windmill ($\Omega R/V = 5$). Therefore, modern, high-speed windmill designs have blades closely resembling those of a helicopter with all the accompanying flexure and vibration problems.

Although a lot of design information can be gained from a steady flow analysis, there are additional complicating factors of unsteady wind speed and the vertical wind profile to deal with also. Early Dutch research showed that operation in an unsteady wind meant that maximum average power output depended on both the steady and unsteady characteristics of the windmill. Depending on the wind fluctuations, power output can be quite unsteady, and there is a minimum value of wind speed below which operation ceases altogether. This has important mechanical design implications as well as an

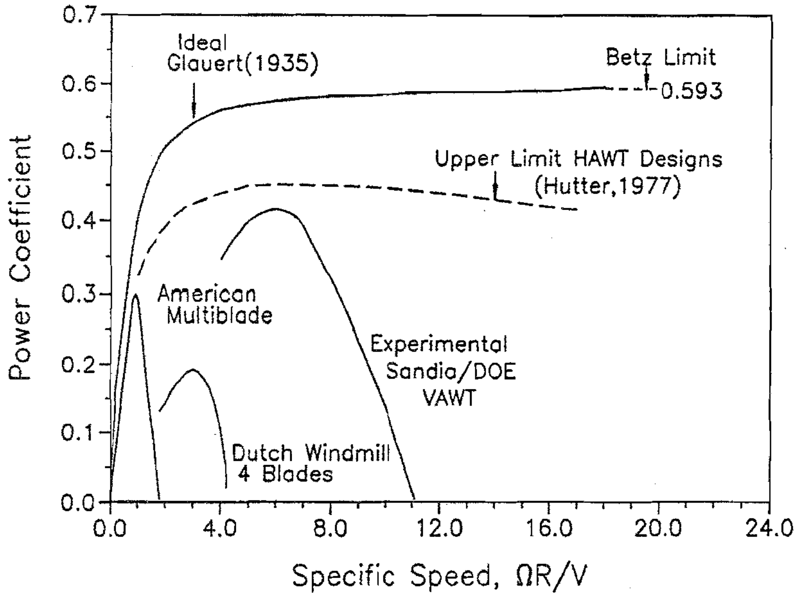

FIGURE 41.34 Power coefficient as a function of specific speed. Adapted from data in Hütter (1977) and Spera (1994).

important influence on the economic analysis of a wind power system. Early Dutch research indicated that the average power could be optimized when the rate of change of tip speed with wind velocity is optimized. It can be shown that

$$\frac{d(\Omega R)}{dV} = \left[\frac{\rho R^4 V}{I}\right] t \tag{41.56}$$

where I is the moment of inertia for the rotor and t is a time constant related to the wind fluctuations. Classic Dutch windmills apparently have optimum output when the moment of inertia is such that $I/\rho R^4 V$ is about 1 s. Several poorly operating mills in Holland have been improved by simply adding lead weights to the tips of the sails to increase the moment of inertia.

Much more sophisticated methods of handling fluctuating loads are used in modern wind generators. Constant speed units that have hydraulically actuated blades for variable pitch can be designed in a manner similar to the familiar constant speed propeller on an airplane. Nonuniformities in loading with blade position due to the vertical wind profile can be handled in the same way that nonuniformities in blade loading are handled on a helicopter.

Design Issues

Most wind velocity data have been collected at airports, which are not necessarily the best wind-power sites. In spite of this limitation, estimates that take the variation of wind speed with time into account indicate that the resource is distributed very nonuniformly. Not only is the distribution of wind power over the earth's surface quite nonuniform, there are also distinct seasonal and daily variations. This is illustrated in Fig. 41.35, which is the cumulative distribution of wind speed at three different sites: a very poor U.S. site, a U.S. site with excellent potential, and the summer and winter variation in the North Sea off the coast of Holland. Because of the cubic dependence of power on wind speed, the variations in wind power are greatly magnified. Although there is great potential use of wind power, there are serious problems with its variability. Proper site selection is crucial and imaginative design is necessary to smooth out the variations in power output. Because of the relatively small density of air, economic designs are

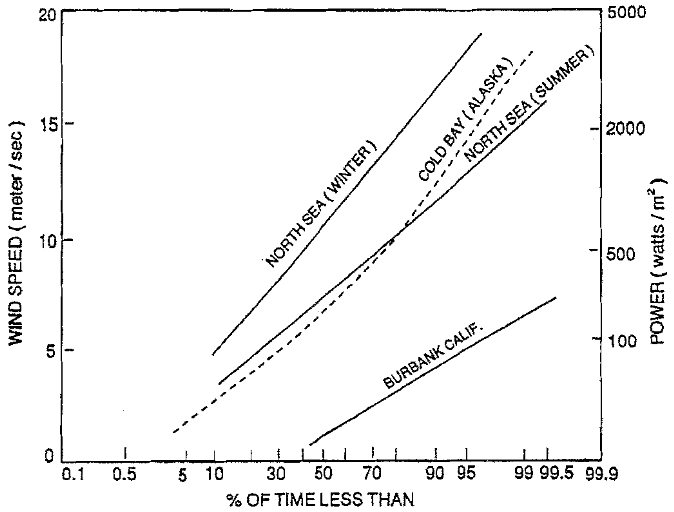

FIGURE 41.35 Cumulative distribution of wind speed at three different sites.

often very large. A typical 1 MW unit designed for a wind speed of 15 m/s would have to be 40 m in diameter. The structural and aerodynamic design of such a unit is challenging because of the relative flexibility of the blades and high dynamic loads on the support structure. A significant variation in wind speed over the swept area of the blades causes severe vibration and control problems.

Environmental concerns are noise and interference with television signals. In the case of high capacity systems, extensive land use requirements and visual pollution could be important, but have not been considered at this time.

Defining Terms

Actuator disk: A theoretical rotor having an infinite number of frictionless blades that creates a pressure rise without a change in velocity.

Specific speed: Has the same physical interpretation as in other turbomachinery. Defined as the relative tip speed, $\Omega R/V$.

Disk area: Is the area swept by the rotating blades, $A = \pi R^2$.

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