SCIENTIFIC

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Classification and characteristics of wind turbines (wind engines)

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ABSTRACT:

The document presents an algorithm for linking the wind speed vector with the wind turbine's (wind engine's) power output and efficiency. Different wind engine desings and their efficiency have been discussed. Wind turbines have also been divided according to their power output and use cases for individual power ranges have been specified.

Klasyfikacja i charakterystyka turbin wiatrowych (silników wiatrowych)

Słowa kluczowe: współczynnik mocy turbin wiatrowych, podział turbin wiatrowych, kinematyka turbiny wiatrowej

STRESZCZENIE:

W pracy przedstawiono algorytm matematyczny powiązania wektora prędkości wiatru z mocą wiatrową turbiny wiatrowej (silnika wiatrowego) oraz jej sprawnością. Omówiono podział konstrukcyjny silników wiatrowych i przedstawiono ich sprawność. Dokonano również podziału turbin wiatrowych w stosunku do ich mocy i podano zastosowanie dla poszczególnych przedziałów mocy.

1. INTRODUCTION

Wind power has been accompanying human beings from the beginning of the civilisation to the present day. It has been the oldest renewable energy used by people, alongside the combustion of wood. At first wind energy was used to move ships and boats. The first mentions of sailing vessels originate from the ancient Egypt – they were used to transport stone blocks on the Nile for the construction of the pyramids [1, 2]. The most important innovation among the European drive units, however, was the windmill.
The origin of the European windmill is another secret. The windmill was initially used by man to mill the grain and pump water. The first description of their use for pumping water was developed around 400 BC in India and Persia [2, 3]. During the 1st century AD Heron from Alexandria suggested that the hydraulic organ be driven by a small windmill. The Heron's windmill rotated on the horizontal axis. Nine centuries after the Heron's small turbine in Sistan, wind-driven mills were used, which is confirmed in the statement of an Arab geographer and historian Al Masudi, made in 947: "Sistan is the land of wind and sand". Nowadays, especially in the last two decades, there has been rapid development of wind technology as a source of energy, comparable even to IT development. In this case, environmental factors pertaining to CO2 emissions as well as economic factors were particularly considered.
The device that converts wind energy into mechanical energy at each wind power plant is the wind turbine, also known as the wind engine. One of the basic characteristics of the wind turbine is its power factor Cp which is the ratio of the turbine power output to the total wind power. The turbine power factor depends on the design parameters which may include the number of blades and their profile. This factor also depends on the rotational speed of the rotor and instantaneous wind speed, and in turbines with a horizontal axis of rotation also on the current angle of the turbine blades [4, 5].
Each type of the wind turbine has a specific Cp value.

2. WIND TURBINE (WIND ENGINE) KINEMATICS

Wind speed vector upstream of the turbine rotor is higher than wind speed downstream of the turbine. It results from the fact that a portion of energy in the form of an air stream flows behind the turbine rotor. If 100% of the wind power was to be removed, however, the speed of the outgoing air would have to be zero. As a result, the turbine would not produce any energy. In the second limit case, the air flow might not change its velocity after contact with the turbine. In this case the power output would be zero, too.
The air encloses the turbine as shown in Figure 1. The amount of air flowing in per second at a speed of V_1 (from the right) must be equal to the amount of air flowing out on the left side with a reduced speed of V_2.
As the condition of stream continuity must be maintained for the flowing gas:

$$A_1 \cdot V_1 = A_2 \cdot V_2 , \tag{1}$$

where:
A_1 – surface determined by the rotor in m^2
A_2 – air stream surface downstream of the rotor in m^2
V_1 – wind speed upstream of the turbine rotor in m/s
V_2 – wind speed downstream of the turbine rotor in m/s

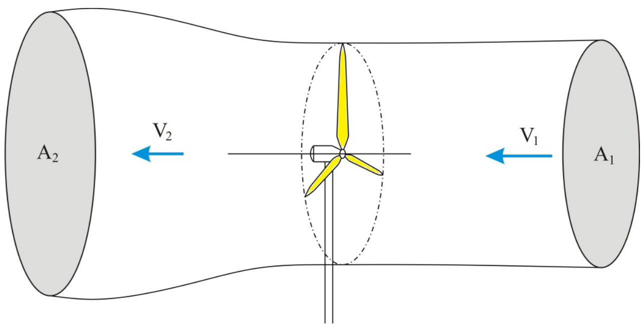

Figure 1 Air flow through the turbine [4]

therefore, the surface A_2 must be increased to the extent equal to the decrease of speed [5, 6].
Air mass flowing through the rotor within one second:
where:

$$m = \rho \cdot A_1 \cdot \frac{V_1 + V_2}{2} , \tag{2}$$

ρ – air density in kg/m^3.

The wind power is:

$$P_{ow} = \frac{m \cdot (V_1^2 - V_2^2)}{2}, \quad (3)$$

and after replacing m in the equation (2), the equation is as follows:

$$P_{ow} = \frac{\rho}{4} \cdot (V_1^2 - V_2^2) \cdot (V_1 + V_2). \quad (4)$$

The wind power is equal to:

$$P_{zw} = \frac{1}{2} \cdot \rho \cdot A \cdot V_1^3. \quad (5)$$

The ratio of the wind power and the power to be received is:

$$\frac{P_{ow}}{P_{zw}} = \frac{1}{2}(1 - \left(\frac{V_2}{V_1}\right)^2) \cdot (1 + \frac{V_2}{V_1}) = C_p. \quad (6)$$

This ratio is known as the Betz coefficient of power C_p. The Cp was determined for the first time by Albert Betz in 1919 [4]. When testing the Betz function, it is possible to calculate the optimum change in the velocity of the air flow through the wind turbine rotor in order to absorb the maximum amount of the wind power. Calculating the derivative of the equation (6) using the variables V_2/V_1 and equating it to zero, the following maximum value [4, 7] is given:

$$\left(\frac{V_2}{V_1}\right)_{opt} = \frac{1}{3}. \quad (7)$$

The highest power is obtained when the ratio of V_2 to V_1 is 1/3. The highest achievable wind power is 16/27 of the total wind power. Theoretically it is not possible to obtain more than 59.2% of power from the available power contained in the flowing air stream. Figure 2 illustrates the waveform of the Betz coefficient relation to the speed ratio V_2/V_1. As can be seen, the function reaches the extremum where this ratio is 1/3, and for higher and lower values it takes lower values.

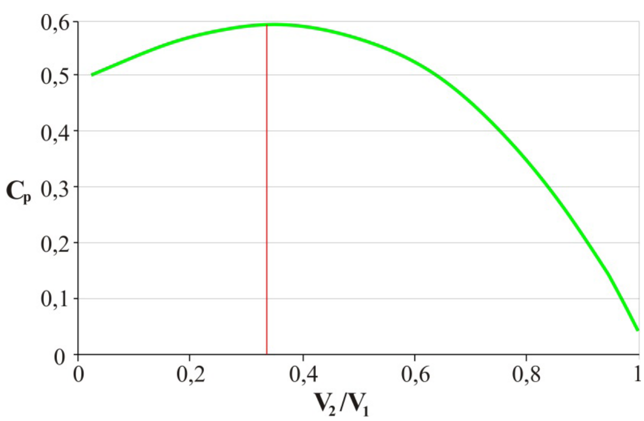

Figure 2 Betz coeffient of power C_p [4]

The C_p coefficient is usually lower in practice since the theory does not take into account all factors affecting the operation of the turbine and all losses. Figure 3 shows the curve of the C_p coefficient as a function of the tip speed λ for a given turbine type. The wind power is best used by a two-blade wind turbine with a horizontal axis of rotation since its aerodynamic efficiency C_p is within the range of 46%. The lowest efficiency has the Savonius turbine with a vertical axis of rotation – it uses wind energy in ca. 20% [4, 6 and 7].

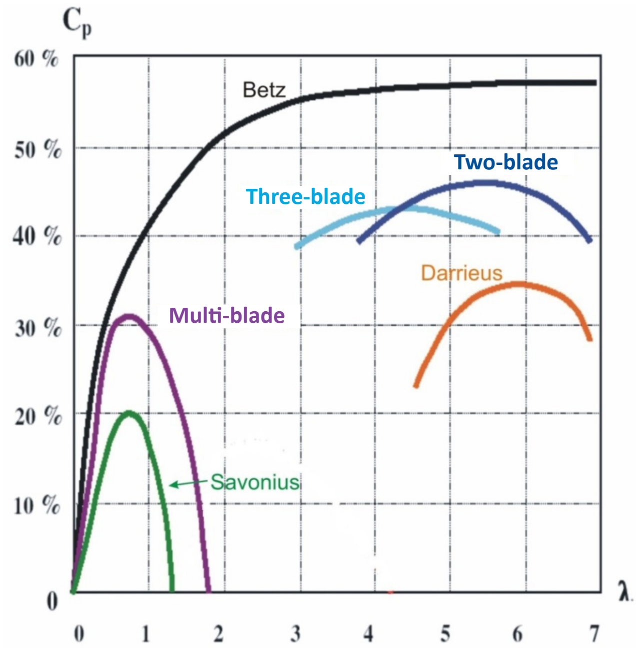

Figure 3 Relation of C_p coefficient to the wind turbine tip speed λ [6]

$$\lambda = \frac{0{,}5D \cdot \omega}{V_1}, \quad (8)$$

where:

ω – angular speed of the turbine rotor

D – turbine rotor diameter.

3. CLASSIFICATION OF WIND TURBINES IN TERMS OF POWER OUTPUT

The next parameter characterising the wind turbines is the power output which is decisive in the application:

1. Micro wind power plants – have power output lower than 100 W. They are usually used to supply power to batteries for lighting of individual rooms or devices at home, and recently also to supply road and municipal infrastructure.
2. Small wind power plants – have power output ranging from 100 W to 50 kW. Such power plants

may provide electricity for individual households or even small companies. The market demand for this type of equipment has increased in recent years.

3. Large wind power plants (in practice with power output between 100 kW and 1 MW), apart from being able to feed households, are mainly used to produce electricity that is sold to the power grid.

4. Max. wind power plants – have rated power output above 1 MW. They are mainly used is the energy industry – in the so-called wind farms located both on-shore and off-shore.

4. CLASSIFICATION OF WIND TURBINES (WIND ENGINES) IN TERMS OF DESIGN

The design factor, which constitutes the next classification of wind turbines, is the axis of rotation of the rotor. Wind turbines with a horizontal and vertical axis of rotation can be distinguished. Wind turbines with a horizontal axis of rotation (*horizontal-axis wind turbines*) (Fig. 4) are widely known. The most common turbine belonging to this group is the three-blade rotor used in commercial wind power plants (wind farms). It utilises wind speed range of 4 to 25 m/s. When the maximum wind speed value is exceeded, such a rotor is shut down for design safety reasons (high centrifugal forces could destroy the rotor blades).

The multi-blade windmill was widespread in North America as a source of propulsion for water pumps. It is characterised by the use of small wind gusts, it is a low-speed turbine and has a high starting torque as compared to the three-blade rotor. Its advantages include low-noise operation.

The diffuser rotors and rotors using the Magnus effect are not widespread; only a few such designs exist worldwide. All horizontal-axis turbines must be equipped with a wind positioning system as they can operate only if the wind speed vector is parallel to the turbine rotor rotation axis [8, 9, 10].

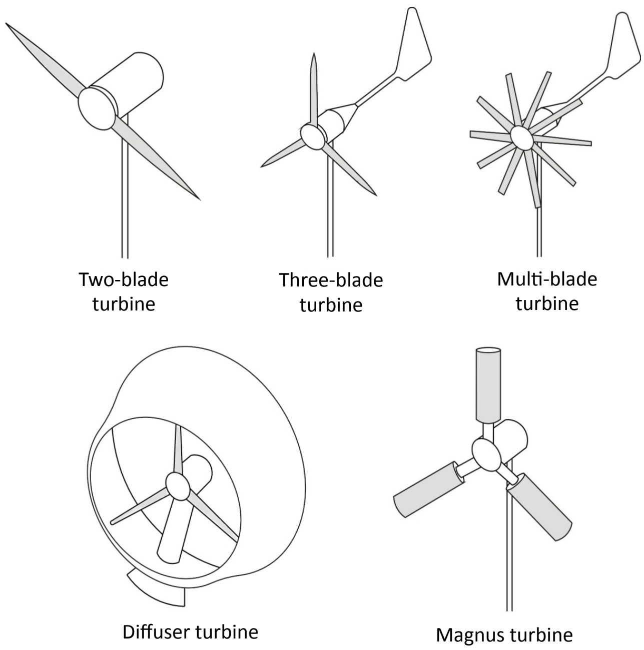

Figure 4 Wind turbines with horizontal axis of rotation (*horizontal-axis wind turbines*) [8]

5. SUMMARY

Power generated by the wind turbine depends on the wind speed vector, which is the main issue in the forecasting of energy generated by wind farms one week in advance in order to manage the energy demand on a given day. However, this does not impede the development of this power sector and the market demand for wind energy. It should be noted that there are many methods of application of wind microturbines, e.g. in road infrastructure, in conjunction with photovoltaic panels (these two sources of electricity complement each other); they are also seen in holiday homes and on yachts.

An increasing number of wind turbines with power over 2 MW have been located off-shore in recent years to make best use of wind energy. In this location the roughness of the area is the most advantageous (the wind speed vector is parallel to the water surface, it is not disturbed by ground and urban-related obstacles).

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