SOME ASPECTS OF INCREASING WIND TURBINE CONVERSION EFFICIENCY

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"First, there is the power wind, constantly exerted over the globe... Here is an almost incalculable power at our disposal, yet how trifling the use we make of it"
(Henry David Thoreau)

1. INTRODUCTION

Wind energy has been used by mankind over thousands of years. For over 3000 years the windmills have been used for pumping water or grinding (milling). Nowadays, in the century of information technologies, nuclear energy and electricity, thousands of windmills are used for pumping water and oil, for irrigation and production of mechanical energy to drive low-power mechanisms on different continents.

With the launch of the European Technology Platform on wind energy issues the EU Commissioner A. Piebalgs said [1]: *"Wind energy technology is certainly one of the fastest growing and plays an important role, contributing to create a sustainable and competitive energy policy in Europe"*. Nowadays, the phrase *"use of wind energy"* means, primarily, non-pollutant electrical energy produced at a significant scale by modern *"windmills"* called *"wind turbines"*, a term that attempts to outline their similarity to steam or gas turbines, which are used for producing electricity, and also to make a distinction between their old and new destination. If in 1973 the main incentive for the development of WECS was the oil price, today another incentive is added - the tendency of mankind to produce "*clean*" or "*green*" electricity with little or no carbon monoxide emissions. The year 1993 was marked as the beginning of a wind boom characterized by an annual increase of over 20% of installed power capacity. Thus, in 1999 the global capacity increased by 4033 MW, which was a record for the wind energy sector [2]. In the period 1996-2016 the global wind power cumulative capacity has increased about 80 times

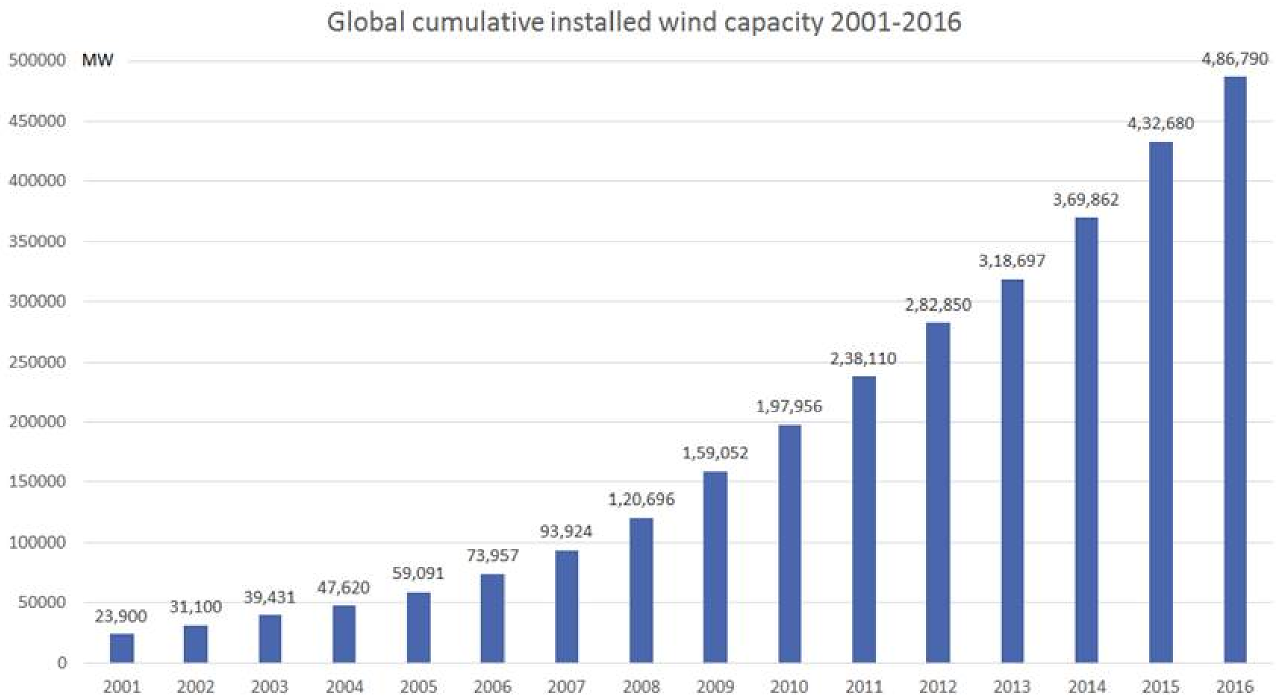


Figure 1. Global Wind Power Cumulative Capacity (Data: GWEC) [1].

and has reached 486,8 GW in 2016, up 12% from 2015 (Figure 1) [3].

The undisputed global leader is the European Community EU-27 with a 65% share, followed by the China and USA. 2015 was a record year for wind energy generation in the U.K, according to National Grid. National Grid's statistics show that 11 percent of the U.K.'s electricity was generated by onshore and offshore wind; last year – up to 9.5 percent in 2014. The newly installed turbines brought the country's total wind capacity to 13,602.5 MW and the U.K. has an installed onshore wind energy capacity of 8.5 GW and offshore wind energy capacity of 5.1 GW, onshore wind capacity built in the past year was down from 1.1 GW [4]. Germany and India continued to be the most important actors. Also, Brazil has achieved the highest growth rates in all major markets. Africa, Asia and Latin America will become the market leaders of the next decade [4].

Very important result in the field was obtained by some small countries. In July, 2017 Wind power production in Lithuania soared by 40 percent in the first half of 2017 year-on-year to 633 gigawatt-hours (GWh), accounting for half of the country's total electricity output during the six months [5].

Such a spectacular development knows no other global industry sector worldwide. In the years 2007-2010 an annual growth over 21% was expected. In fact, annual growth was of 35% on average. For 2010 the global installed capacity should have reached 160,000 MW. In fact, the total value of 197,000 MW has been reached, with more than 25% over the initial estimates. Germany connected 626 MW of newly built offshore wind capacity to power grids in the first six months of this year and expects to see total installation of 900 MW in the full year [6].

Global wind power installations will nearly double in the next five years as prices continue to fall and countries develop renewable energy to comply with emissions reduction targets, according to research published in Global Wind Energy Council (GWEC) flagship publication.

GWEC secretary-general Steve Sawyer said: "*Wind power led all technologies in new power generation in 2015. Led by wind, renewables have come of age and are transforming the power sector*".

The global wind revolution was led by the Chinese industry, which installed 30.8 GW of new capacity and increased its cumulative capacity to 145 GW. Europe had a strong year thanks to Germany's record-setting 6 GW of installations, while the US ended the year with a "*surprisingly high*" 8.6 GW market.

The wind power industry is moving away from an era of costly subsidies and is trying to become more commercially viable and to bring down costs for consumers. The industry groups said that latest bids by companies to build and run turbines at zero subsidy costs in the next decade offered encouragement and reason to expand. "*This paradigm shift offers the next government chances to lift expansion targets to at least 20 gigawatts (20,000 MW) up to 2030 and at least 30 GW to 2035, utilizing the economic and industrial political potential of offshore wind,*" said the president of *HelWin-Cluster* located in Germany [6].

2. INCREASING POWER AND CONVERSION EFFICIENCY OF THE MEGA-WIND TURBINE

These major results have been achieved largely due to the optimization in terms of conversion efficiency in mega-wind turbines, the increase in power of a mega-wind turbine, and the reliability of the basic element of a mega-wind turbine – the blade. New research on the dynamic response of the blade in the turbulence phases opens up great prospects for the development of very powerful wind turbines. Currently wind turbines with a power in the range 1.1-2.5 MW are used to form wind farms. But the current solid trend is to increase the power of a wind turbine. Thus, the American company VESTAS switched to the production of wind turbines of 3.3 MW (from 2 MW) turbine installed power [7]. The German company Siemens has assimilated series production of optimized lightweight turbines of 3.3 MW for low wind speeds. Currently, turbines with a power of 5 - 6 MW are the most used. The British company "DONG Energy Gunfleet Sands" has announced that it installs two turbines of 6 MW each, produced by Siemens [8].

Lately, several daring projects have emerged aiming to overcome this power limit for a wind turbine. Thus the American company "Winter Wind Propels Texas" has reached a new record of 9.481 MW for a turbine [9]. Siemens will be supplying wind turbines for a 16-MW wind farm owned by the clean energy firm BayWare GmbH in Sweden [10].

An absolute world record seems to be attained by Danish researchers. Following five years of research at the joint European project UpWind, led by Risø National Laboratory for Sustainable Energy, the Technical University of Denmark (Risø DTU), scientists have now presented the first design basis for developing mega wind turbines of 20 MW [10]. The researchers focused on the main components in wind turbines to find answers to two fundamental questions: Is it technically possible to build a 20 megawatt wind turbine? Is it economically feasible to build it? An intelligent wind turbine blade is one of the solutions. Risø DTU and DTU Mechanical Engineering have significantly contributed in the development of aeroelastic design methods for wind turbines of up to 20 MW. Aeroelastic methods are used to calculate the wind turbine's dynamic response to turbulence in the wind. In the UpWind project, Risø DTU and DTU Mechanical Engineering studied aeroelastic methods, materials, management and regulation and many other technologies to be developed for designing a 20 MW wind turbine [10]. "*We have worked on developing several different types of sensor systems such as pitot tubes which are also used to measure the wind speed of aircrafts. Should we introduce these innovations to existing wind turbines, they would probably be more expensive, but if they are implemented on very large turbines the savings from load reductions probably would be competitive. Our conclusion is that upscaling opens up for new technologies*", says Peter Hjuler Jensen, researcher from Denmark Technical University [10].

It is noticed that the blade becomes an important object to be sudied in the plan to increase the power of a turbine. In the same context, the authors come up with an original idea to increase the wind turbine power by installing the blade at a certain downstream angle in the rotor hub (Figure 2) [11].

The wind turbine with horizontal axis comprise a tower (4), on which are installed a rotor (2) with three aerodynamic blades (1), located on the hub of the rotor (2) at an angle θ relative to the vertical plane of the rotor (2), the value of which is determined by the formula:

$$\theta = 2arcsin\frac{y_{max}}{D} = 2arcsin\frac{F_{max}\left(\frac{D}{2}\right)^3}{D3EI_y} = arcsin\frac{F_{max}D^2}{12EI_y}, \quad (1)$$

where: y_{max} is the amplitude of displacement of the blade tip; D - rotor diameter; F_{max} - maximum deflecting force; E - modulus of elasticity of blade material; I_y - the moment of inertia relative to the axis of symmetry of the blade's aerodynamic profile. The distance from the vertical plane of rotation of the blades 1 to the outer surface of the tower 4 is minimal.

The horizontal axis wind turbine operates in the following manner: the action of the wind currents on the aerodynamic profile blades 1 generates the aerodynamic effect, which drives the blades 1 in rotation motion transmitted to the rotor 2. If the blades 1 are located perpendicular to the rotor shaft 2 at the distance A (Figure 2) from the vertical plane of rotation of the blades 1 to the outer surface of the tower 4, at low wind speeds, the blade 1 is practically unwarped, and the rotatable area of the rotor 2 is determined according to the formula:

$$A = \frac{\pi D_0^2}{4}, \quad (2)$$

And the generated power is determined according to the formula:

$$P_0 = \frac{1}{2}kpV^3A_0 , \quad (3)$$

Where: k is conversion efficiency; ρ – air density; V – air speed; D_0 - wind rotor diameter.

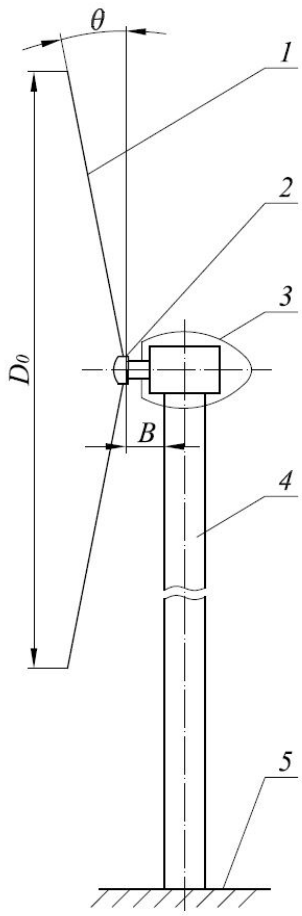
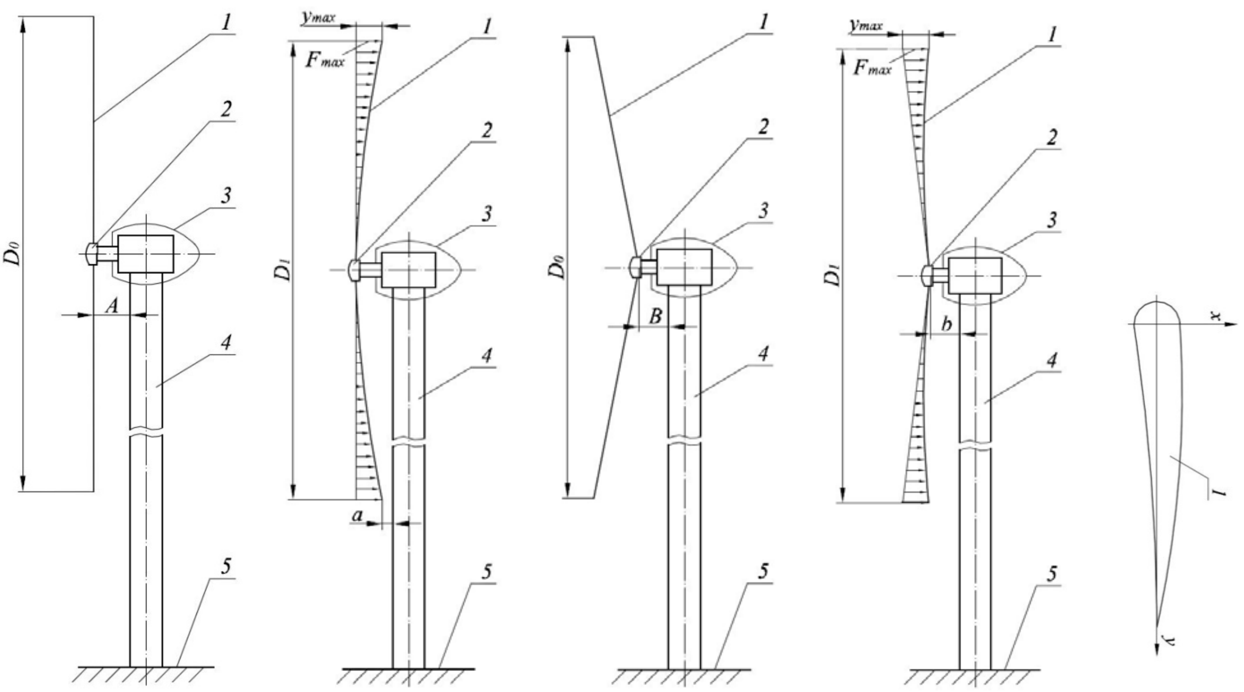


Figure 2. Wind rotor with vertical installed blades [11].

At high wind speeds, the blade 1 warps (Figure 3, b) at the distance *a* from the tip of the blade 1 to the



a. ***b.*** ***c.*** ***d.*** ***e.***

Figure 3. Calculus diagrams for a blade installed with no downstream bending angle (a, b) and with downstream bending at the angle θ (c, d); the coordinates of the blade in normal section (e).

outer surface of the tower 4, its tip moving as indicated by the arrow y_{max}, which is determined according to the formula:

$$y_{max} = \frac{F_{max}\left(\frac{D^0}{2}\right)^3}{3EI_y}, \quad (4)$$

where: F_{max} is maximum bending force generated by wind currents acting on the blade 1; D_0 - wind rotor diameter; E – elastic modulus, first degree, of the blade 1 material; I_y – moment of inertia of the blade 1 section against the axis "y" (Figure 3,e).

The rotatable area of the rotor 2 is determined according to the formula:

$$A_1 = \frac{\pi D_1^2}{4}, \quad (5)$$

Where $D_1 = D_0 cos\theta$, and $\theta = 2arcsin\frac{y_{max}}{D_0}$.

The generated power is determined according to the formula:

$$P_1 = \frac{1}{2}kpV^3A_1. \quad (6)$$

If the blades 1 are located at an angle θ downstream of the vertical plane of the rotor 2 at the distance *B* from the vertical rotation plane of the blades 1 to the outer surface of the tower 4, at low wind speeds, the blade 1 is practically unwarped (Figure 3, c), and the rotatable area of the rotor 2 is determined according to the formula:

$$A_0 = \frac{\pi D_1^2}{4} = \frac{\pi(D_0 cos\theta)^2}{4}, \quad (7)$$

In this case converted energy is determined according to the formula (3).

At high wind speeds, the blade 1 warps (Figure 3, d) at the distance *b* from the tip of the blade 1 to the outer surface of the tower 4, its tip moving as indicated by the arrow y_{max}, which is determined according to the formula:

$$y_{max} = \frac{F_{max}\left(\frac{D_1}{2}\right)^3}{3EI_y}, \quad (8)$$

The rotatable area of the rotor 2 is determined according to the formula:

$$A_1 = \frac{\pi D_0^2}{4}. \quad (9)$$

Converted energy is determined according to the formula (6).

Thus, when bending the blade tip at an angle below 7^o the rotor diameter will decrease by approx. 2%, and consequently, the converted wind power will also decrease by 2% (in the calculus formula, the power is directly proportional to the rotatable area of the rotor), which for an installed turbine power of 5 kW represents approx. 100 kW.

CONCLUSIONS

The comparative analysis of the two examples demonstrates that, when installing the blades 1 at the angle θ downstream of the vertical plane of the rotor 2, at high wind speeds (when the energy potential is high) the blade 1, by warping, gets in a position close to the vertical one, thus enlarging the rotatable area, therefore also the amount of converted energy.

By placing the blades 1 on the hub of the rotor 2 at the angle θ, once warped under the action of wind currents at high wind speeds, the blades 1 will get in a position close to the vertical one. Therefore, in order to avoid collision between the blades 1 and the tower 4, the plane for installing the blades 1 in the hub is closer to the outer surface of the turbine tower 4 (B<A), which results in reduced bending moment generated by the forces acting on the blades 1 at high wind speeds. This in turn ensures lower stress on the mobile elements that connect the wind rotor 2 and the nacelle 3 to the tower 4. There also occurs a reduction in the forces acting on the bolts that fasten the tower 4 to the basement 5.

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