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Aerodynamic Characteristics of a Horizontal Axis Wind Turbine in Belen-Hatay, Turkey

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Abstract

Wind turbine aerodynamic characteristics play a vital role in condition monitoring and control of wind turbines in a wind power plant. Today, the most common design of wind turbine is the horizontal axis wind turbine. In this study, horizontal axis wind turbine aerodynamic characteristics including wind power (P), power coefficient (C_P), axial flow induction factor (a), thrust coefficient (C_T) and thrust (T) were determined as a function of the hub-height wind speed. The data used in this study were measured from the Belen Wind Power Plant which is located in Belen province in Hatay, Turkey and the total installed capacity of that power plant is 48 MW which is composed of 16 turbines. The 5 of 16 turbines were evaluated by means of aerodynamic characteristics in detail. As a result, for 5 turbines, the maximum wind power capacity reached 3 MW when the hub-height wind speed was 15 m/s. Also, maximum power coefficient of all turbines was calculated to be 30% - 35%.

Keyword: Aerodynamic characteristics, Power Coefficient, Wind speed, Wind power.

INTRODUCTION

Wind power is predicted to have the greatest future prospects among the possibilities for renewable/sustainable energy [1-3]. Without decisive action, energy related greenhouse gas emissions could go up more than double by 2050, and increased oil demand will heighten interest over the security of supplies. For this reason, an energy revolution is needed to achieve a 50% reduction of global CO_2 emissions relative to current levels by 2050. In this revolution, energy efficiency, sustainable and low-carbon energy technologies play a crucial role in the energy sector. In addition, renewable energy plays a significant role in addressing global energy and environmental challenges [4]. Among renewable energy sources, wind is the most advanced of the new renewable energy technologies. In a few countries, wind power already provides 15% to 30% of total electricity. The technology has been growing rapidly, and costs of generation from the land-based wind installations have continued to fall [5]. There is now 370 GW of installed wind power capacity in the world and a total of 128.8 GW is now installed in the European Union as seen in Figure 1 [6].

Production of energy affair in Turkey by recent years boosted dependency on abroad as in natural gas and consequently unbalances in energy productions grew out. Wind energy which is a category of renewable energy source has a great potential in Turkey, however we cannot presently benefit from this potential sufficiently in reality [1].

A new installation of wind power with the capacity of 804 MW was installed in 2014 increasing the total installed capacity to a value of 3,763 MW in Turkey. Namely, Turkey's installed capacity has grown up with amount of 500 MW per year since 2010. Turkey's National Transmission Company expects annual installations to reach 1,000 MW per year starting from 2015 onwards. Turkey's best wind resources are located in the provinces of Çanakkale, Izmir, Balıkesir, Hatay, Osmaniye and Istanbul. By the end of 2014, the Aegean region had the highest installed wind capacity with a total of 1,486 MW, followed by Marmara region with 1,359 MW and the Mediterranean region with 543 MW. The Turkish Wind Energy Association expects Turkey to reach an installed capacity of 5.000 MW by the end of 2015 and 6.200 MW by 2016. Presently, Turkey is one of the biggest on-shore wind markets in Europe with an 11 GW capacity of wind power projects [7].

As seen, wind energy is developing towards a mainstream, competitive and reliable power technology. Globally, progress of wind power technology continues to be strong in further involved countries and increases annual installed capacity having more investments. According to the International Energy Agency [8], wind power could generate up to 18% of the world's electricity by 2050, compared with 2.6% today. Technology improvements have continuously reduced energy costs, especially on land. A lot of wind turbines are being constructed to obtain energy from wind. However, regions which have high wind energy density are finite. Therefore, many researches make an effort to increase energy efficiency of wind turbines. In this context, wind turbine aerodynamic characteristics are important tools in turbine performance monitoring, turbine control and power forecasting [4]. Generally, horizontal axis wind turbines (HAWT) having a single rotor is used for conventional wind turbine systems. In this study, aerodynamic characteristics of HAWT including P, C_P, a, C_T and T were determined as a function of the hub-height wind speed.

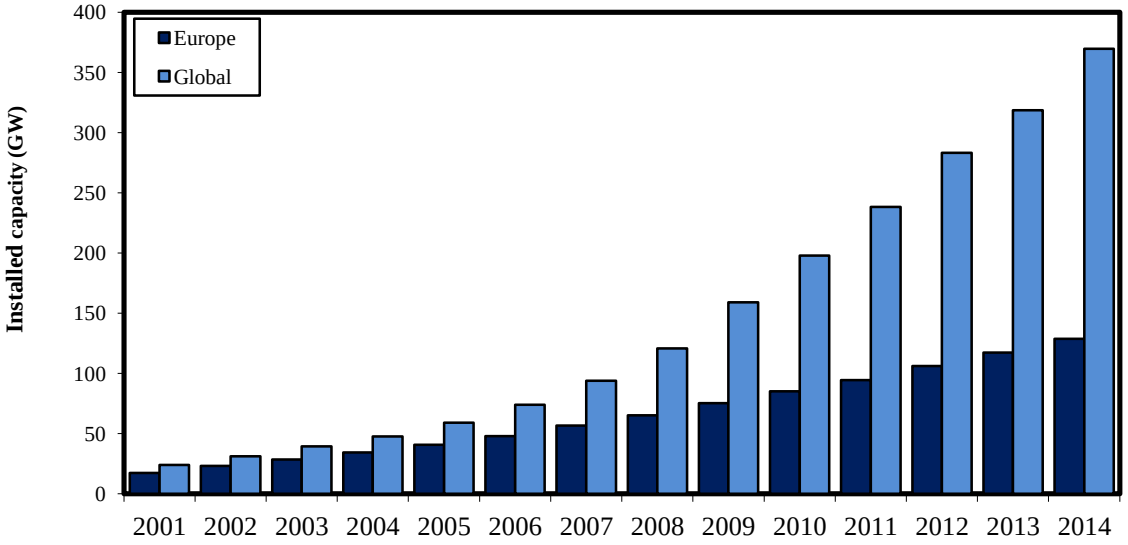


Figure1. Development of wind power installed capacity in the world and Europe

MATERIAL AND METHODS

Study area and data description

The data used in this study were measured from Belen Wind Power Plant (WPP). Belen WPP is in the Hatay, Turkey and was put into operation in 2009. In the first phase, installed capacity of the plant is 30 MW. In 2010, the 6-MW capacity expansion provided with temporary admission, thus Belen WPP has reached 36 MW. Total installed capacity of Belen WPP has increased 48 MW with 4 extra turbines in 2012 and annual production amounts to about 150 million kWh. Belen WPP includes 16 identical wind turbines with the rated capacity of 3 MW and the hub height of 80 m. The cut-in speed, rated speed, and cut-out speed of the turbines are 4, 15, and 25 m/s, respectively. Turbines of WPP are the Vestas V90-3 MW wind turbine types. The VESTAS V90-3 MW wind turbine is a pitch regulated upwind turbine with active yaw and a three-blade rotor. It has a rotor diameter of 90 m with a generator rated at 3.0 MW. Five VESTAS V90-3 MW wind turbines (*T1, T2, T3, T4* and *T5*) were selected to investigate the aerodynamic characteristics of related turbines. Important specifications of the three-bladed turbines having hub-height of 80 m are provided in Table 1. The rotor swept area considering 90 m of diameter corresponds to 6362 m^2. Nominal revolutions of the turbines are 16.1 rpm. Operation period of turbines is ranged from 8.6 rpm to 18.4 rpm. Wind turbines operate in a speed interval of $4m/s \le U_d \le 25m/s$. Nominal speed of wind turbines is 15 m/s. Rated output power generation of a single turbine is 3000 kW.

Aerodynamics of horizontal axis wind turbine

An energy extracting actuator disc and stream-tube is illustrated in Figure 2. As shown in this figure, wind turbine power production depends on the interaction between the rotor and the wind. Practical horizontal axis wind turbine designs need airfoils to transform the kinetic energy of the wind into useful energy. The turbine is represented by a uniform 'actuator disc' which creates a discontinuity of pressure in the stream tube of air flowing through it. Note that this analysis is not limited to any particular type of wind turbine. This analysis uses the following assumptions:

- homogenous, incompressible, steady state fluid flow;
- no frictional drag;
- an infinite number of blades;
- uniform thrust over the disc or rotor area;
- a non–rotating wake;
- Static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure.

Table 1. Wind turbine technical specifications

Equipment	**Properties**
Rotor	
Diameter	90 m
Area swept	6362 m2
Nominal revolutions	16.1 rpm
Operational interval	8.6-18.4 rpm
Number of blades	3
Power regulation	Pitch/OptiSpeed
Air brake	Full blade pitch by three separate hydraulic pitch cylinders
Tower	
Hub height	80 m
Operational data	
Cut-in wind speed	4 m/s
Nominal wind speed	15 m/s
Cut-out wind speed	25 m/s
Generator	
Type	Asynchronous with OptiSpeed
Rated output	3000 kW
Operational data	50 Hz, 1000 V
Gearbox	
Type	Two planetary and one helical stage
Control	
Type	Microprocessor-based control of all the turbine functions with the option of remote monitoring. Output regulation and optimization via OptiSpeed and OptiTip pitch regulation

As seen from Figure 2, the disc upstream of the stream-tube has a cross-sectional area smaller than that of the disc and an area larger than the disc downstream. During a steady-flow process, the total rate of mass entering a control volume is equal to the total rate of mass leaving. The conservation of mass principle can be expressed as [9];

$$\dot{m}_{in} = \dot{m}_{out} \quad (1)$$

$$\rho A_\infty U_\infty = \rho A_d U_d = \rho A_w U_w \quad (2)$$

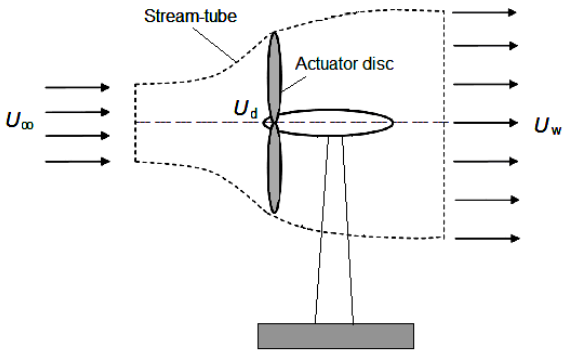


Figure 2. Actuator disc and stream-tube for a wind turbine

Where ρ is the air density, A is the cross-sectional area and U is the wind velocity. The symbol ∞ refers to conditions far upstream, d refers to conditions at the disc and w refers to conditions in the far wake. The actuator disc induces a velocity variation which must be superimposed on the free stream velocity, U_∞ and so the net stream-wise velocity is [9,10]:

$$U_d = U_\infty (1-a) \quad (3)$$

and

$$U_w = U_\infty (1-2a) \quad (4)$$

Where a is called the axial flow induction factor, or inflow factor. The force on the air and the power extraction from the air are calculated by [9,10].

$$T = 2\rho A_d U_\infty^2 a(1-a) \quad (5)$$

$$P = 2\rho A_d U_\infty^3 a(1-a)^2 \quad (6)$$

Power coefficient is defined as;

$$C_p = \frac{P}{\frac{1}{2}\rho U_\infty^3 A_d} \quad (7)$$

or,

$$C_p = 4a(1-a)^2 \quad (8)$$

The maximum value of C_p occurs when

$$\frac{dC_p}{da} = 4(1-a)(1-3a) = 0 \quad (9)$$

that gives a value of a=1/3. Hence,

$$C_{p\max} = 16/27 = 0.593 \quad (10)$$

The maximum achievable value of the power coefficient is known as the Betz limit. The force on the actuator disc caused by the pressure drop can also be non-dimensionalized to give a coefficient of thrust C_T, [9,10].

$$C_T = \frac{T}{\frac{1}{2}\rho U_\infty^2 A_d} \quad (11)$$

$$C_T = 4a(1-a) \quad (12)$$

RESULTS AND DISCUSSION

The variation of wind powers as a function of wind speeds are shown in Figure 3. As seen in this figure, obtained results for whole turbines are in a similar trend based on wind speed, U_d on the rotor. For whole turbines, the maximum wind power was obtained at a wind speed of 15 m/s. The best results were taken from the second turbine, *T2*.

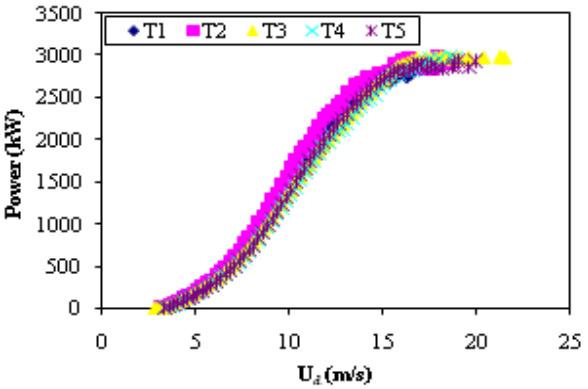


Figure 3. Distribution of power generation, *P* with wind speed, U_d on the impeller

Figure 4 presents the variation of flow induction factor versus U_d on the rotor. Maximum flow induction factors are existed with U_d in the range of $5m/s \le U_d \le 11m/s$. Flow induction factor increases rapidly for $U_d \ge 5m/s$. Similarly, it decreases rapidly for $U_d \ge 10m/s$.

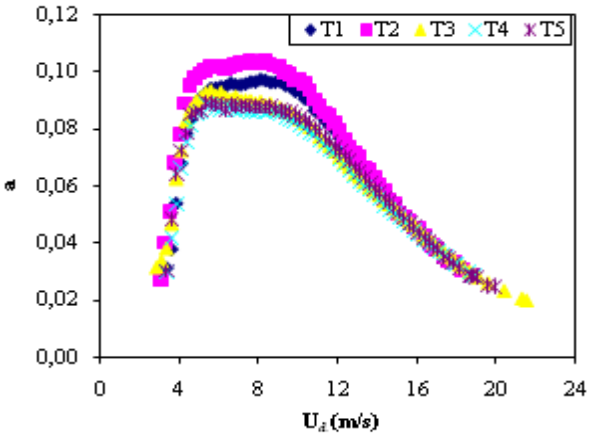


Figure 4. Variation of flow induction factor, *a* with wind speed on the impeller, U_d

Comparisons of C_P with U_d for five turbines are given in Figure 5 and Relations between *CT* and U_d on the rotor were analyzed for five turbines and calculated results were also presented in Figure 6. C_p and C_T are maximum with velocities in the range of $5m/s \le U_d \le 11m/s$. This result indicates that the design of blade is capable of getting maximum power capacity for existing wind speed. But there is power variation between turbines. For example, while turbine, *T2* generates maximum power with percentage of is 34 %, turbine, *T4* produces minimum power with percentage of 29.

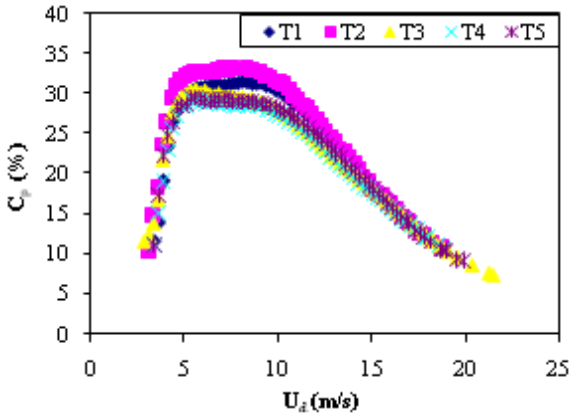


Figure 5. Relation of power coefficient, C_p with wind speed, U_d on the impeller

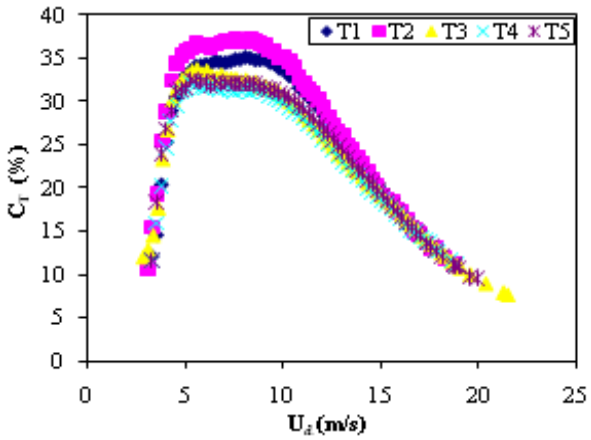


Figure 6. Distribution of thrust coefficient, C_T with wind speed, U_d on the impeller

Variations between *T* with respect to U_d on the rotor are presented in Figure 7. It is seen that the thrust force is extremely important for the performance of wind turbine. Linear variations of the thrust forces depending on the U_d are similar for all turbines for $U_d \le 7.5m/s$. For higher values of U_d, it is obvious that turbine, *T2* generates maximum peak thrust reaching at approximately a value of 200 kN, whereas turbine, *T4* generates minimum peak thrust force about 170 kN. The peak values of the thrusts are generally obtained at approximately U_d corresponding to 14 m/s. In additions, there is a rapid decrease of thrust forces for whole turbines for hub height speeds, U_d which is greater than 14 m/s. Thrust force is presented as a function of U_d with the expression of $T = 2\rho A_d U_d^2 (a/(1-a))$. Consequently, increasing U_d above 14.86 m/s, this U_d^2 can no longer suppress the decreasing trend of a and the expression a/(1-a) where the decreasing trend of both terms start over the values of 8.10 m/s. As a result, U_d equivalent to 14.86 m/s for turbine *T2* is the breaking point where thrust force with respect to U_d rapidly falls down.

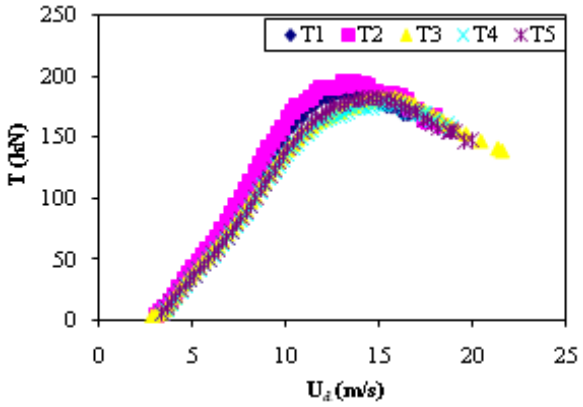


Figure 7. Variation of thrust force, *T* with wind speed, U_d on the impeller

CONCLUSION

Wind power is playing a more significant role in energy supply systems and more sustainable environmental conditions. In this paper, aerodynamic characteristics of horizontal axis wind turbine such as wind power, power coefficient, axial flow induction factor, thrust coefficient and thrust were determined as a function of the hub-height wind speed. The results obtained can be given as follows;

Generated power increases with increasing U_d. Maximum flow induction factors are determined for U_d in the range of $5m/s \le U_d \le 11m/s$. This is also the case in C_p and C_T. Through exceeding the blade speed that is greater than 11 m/s, related parameters of flow, such as *a*, C_p and C_T decrease rapidly. Finally, *T* is maximum with U_d in the range of $12m/s \le U_d \le 14m/s$. Turbine, *T2* generates maximum power with percentage of is 34 %, whereas turbine, *T4* produces minimum power with percentage of 29. Although identical wind turbines are used in the wind farm, there are at approximately %15 differences between maximum and minimum power coefficients. The differences of power coefficient that occur between turbines are due to the obstacles, roughness, wind directions and topographical effects.

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