Wasit Journal of Engineering Sciences
VOLUME: (6), NO. : (2) 2018

Effect of Wind Speed and Blade Deflection Angle on the Output Power of Horizontal-Axis Wind Turbines

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Submitted: 14/5/2017
Accepted: 18/10/2017

Abstract: This study is aimed to optimize the conversion of kinetic wind energy into electrical energy. Wind energy is a sustainable energy that is preferred to generate electricity for its low generation cost and low CO2 emissions. The considerations of physical principles of a horizontal axis wind turbine were involved in the study. Controlling of the blade angle deviation and the turbine rotation direction was also considered. For this purpose, a complete wind turbine system was setup by using the computerized simulation software (PSCAD). The system was running at five different cases with different wind speeds and different angles of the blade. The system was successfully generating a maximum output power from the wind turbine based on the changing of the deflection angle of the blade. Also the system would shut down if there were no matching between the wind speed and its direction with the angle of the blade.

Keywords: Renewable energy, horizontal-axis wind turbine, Kinetic energy, blade angle.

تأثير سرعة الرياح وانحراف زاوية الشفرة على انتاج الطاقة من توربينات الرياح - المحور الأفقي

محمد البدري

الخلاصة:تهدف هذه الدراسة إلى تحسين تحويل طاقة الرياح الحركية إلى طاقة كهربائية. طاقة الرياح هي طاقة مستدامة مفضلة لتوليد الكهرباء لخفض كلفتها وانخفاض انبعاثات ثاني أكسيد الكربون. وشملت الدراسة أيضا اعتبارات المبادئ الفيزيائية للتوربينات الهوائية المحور الأفقي. وفي هذه الدراسة أيضا، أخذت في الاعتبار مبادئ التحكم في زاوية ريشة المروحة واتجاه دوران التوربينات. تم إنشاء نظام متكامل لدراسة توربينات الرياح باستخدام برامج المحاكاة الحاسوبي (PSCAD) لتوليد الطاقة القصوى من توربينات الرياح. تم اعتماد خمسة حالات مختلفة بخمس سرع مختلفة وخمسة زوايا لريشة المروحة التوربينية. أظهرت النتائج أفضل زاوية لريشة المروحة للحفاظ على سرعة الدوار ثابتة مع تغيير سرعة الرياح واتجاهها للحصول على أقصى قدرة انتاج الطاقة الكهربائية المستمرة من توربينات الرياح. بالإضافة إلى ذلك، أظهرت النتائج أن النظام سوف تغلق إذا لم يكن هناك مطابقة بين سرعة الرياح واتجاهها مع زاوية شفرة الانحراف.

I. INTRODUCTION

Perhaps it is now axiomatic to say that the development of ways of exploiting and using renewable energies is one of the most attractive solutions for many countries to address the problems of climate change and its consequences, the increasing demand for energy due to technological development. In addition, achieving strategic security for sustainable energy. Renewable energy source is created from natural procedures that are persistently renewed [9]. This comprises light of sun, heat of geothermal, wind, tides, water and different types of biomass. This energy can't be depleted and is always renewed [5]. Wind energy is of high interest as a renewable energy source that is more environmentally friendly and provides a more useful picture of providing enough energy for many parts of the world.

Wind is generated by the absorption of the surface of the earth, seas and oceans to the sun "Solar Radiation" in varying degrees. When the sun falls, the atmosphere is affected and the air is heated, leading to its low density [1]. As a result, the air moves from the high pressure area (where solar radiation is less) to the low pressure zone (where the solar radiation is higher) leading to the formation of wind, which is the opposite of what happens in areas where the amount of solar radiation is low [5].

Wind turbines are rotary devices that extract energy from the wind and convert it into electrical energy. Mechanical energy was used directly by machinery, for example pumping water, cutting wood or grinding stones, and the machine is called an air mill. If the mechanical energy is converted into electricity, the device is called wind generator, wind turbine, wind turbine power generator (WTG), wind power unit (WPU), and wind power adapter (WPC). Wind turbines can rotate around the horizontal axis or vertical axis, but the first is the most commonly used. The energy potential of the wind corresponds to three basic factors. The first of these factors is wind speed. In fact, the energy in the wind is not proportional to wind speed only but directly proportional to the cube speed of these winds. The second factor is the density of the air, which is a direct relationship. This means simply that the colder the site the higher the air density and the more energy contained in the wind passing by and vice versa. The third factor is the circular area through which the air will pass through the turbine. This means the area of rotation of the blades of the wind turbine itself. This circular space is of course proportional to the square length of the turbo-blades, which represents the radius of the circular area. This explains why we are constantly seeking to increase the size of the turbines and to seek to increase the lengths of the blades of the turbines and thus increase the rotation diameter of the blades of the turbine. Small turbines are extruded for applications such as battery charging or as a backup power or for small boat deserts. Large networks of connected turbines have become a major source of energy production.

Controlling the speed of wind turbine rotor strongly affects the generation of electricity [7]. The capture and variability of energy in variable-speed wind turbines is influenced by the algorithm used to control the wind turbine speed [3]. Based on the characteristics of the electrical grid and the connected loads, the connection of the wind generator system to the grid makes its generating capacity limited [4]. The main idea of this research is that the efficiency of wind turbines can be improved by controlling the speed of the rotor by manipulating the angle of the blades in order to capture more energy from the wind. However, there is no study by far considering the role of altering the blade angles in relation to different wind speeds. Hence, this study is done to investigate the effect of changing wind speeds on the output power of horizontal wind turbines. A systematized model was simulated by using (PSCAD) program. The role of changing the blade deviation angles which affects the efficiency and performance of the wind turbines was also studied.

II. PRINCIPLES DESIGN OF WIND TURBINES

A. The mechanism

The basic principle of the wind generator designs is a rotary part, connected with two or more blades. The rotary group (rotor with blades) is a turbine in the wind generators, which are mechanically engaged with an electric generator. These turbines perform the same work as turbines in the conventional power plants. Several designs have been proposed to increase the energy generated by wind turbines while the modern and the most widespread wind turbines are derived from the old ones [4].

Wind turbines are classified into two main types: a) horizontal axis wind turbines; b) vertical axis wind turbines. Parts of horizontal-axis wind turbine are mechanically engaged together by a shaft, which is parallel to the x-axis. This type of wind generator is always installed on the top of the tower resulting in a high possibility of capturing energy from the wind as shown in Fig. 1. While, parts of vertical-axis wind turbine are mechanically engaged together by a shaft, parallel to the y-axis and its shape is similar to the "egg-beater". The generator of such turbine is always installed on the ground as shown in Fig. 2 [5].

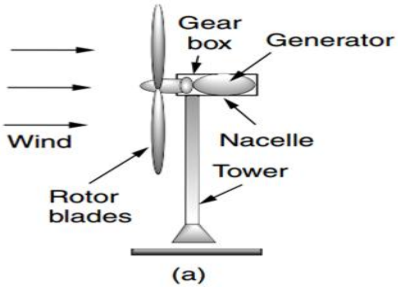

Fig. 1: Horizontal-axis wind turbines [5]

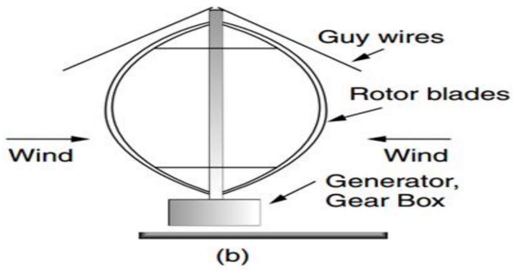

Fig. 2: Vertical-axis wind turbines [5]

The airfoil shapes of the wind turbine blades are either "Drag" or "Lift", which makes it spin or rotate when exposed to wind. Drag-type airfoil is applied to vertical-axis wind turbines, depending on the wind that pushes the blade away [7]. This means that the rotation gets as a result of the difference in the drag forces by the wind because of the convexity and the concavity of the shape of the rotor as shown in Fig. 3. For this reason, these generators are characterized by slow speed and the possibility of high-power torque. Lift-type airfoil is applied with horizontal-axis wind turbines, which is based on the same principle as birds and aircraft in aviation [7].

When a stream of air passes above and below the surfaces of the blade causes in a difference in pressure that surrounding the blade. The pressure below the blade is greater than the pressure above it, leading to lift this blade to the top as shown in Fig. 4. The design of three rotary horizontal wings is predominant since it has proved to be mechanically efficient and it does not cause any noise [7].

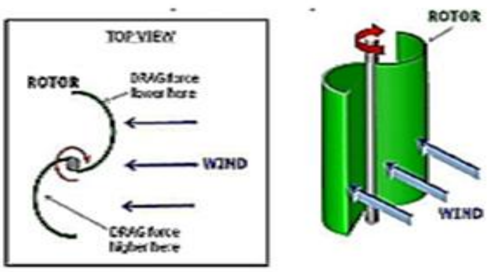

Fig. 3: Drag-type design [5]

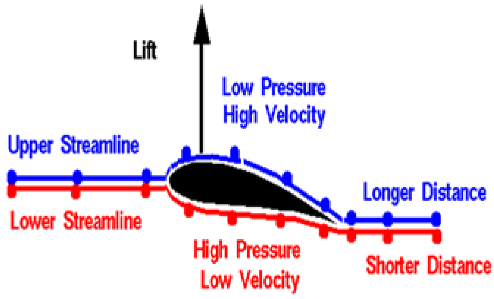

Fig. 4: Lift-type design [5]

B.Control system for horizontal wind turbine

It is essential that large wind turbine has variable speeds to deal with the variations in the wind speed and direction of the wind in order to capture more energy and produce continuous electricity. The speed of these turbines can be controlled either by adjusting the blade angle (pitch-angle) (see Fig. 5) or by rotating the turbines completely (Yaw control, Fig. 6 [4].

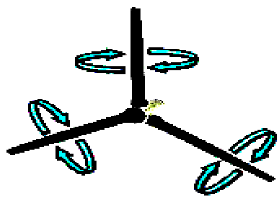

Fig. 5: pitch-Angle Control [6]

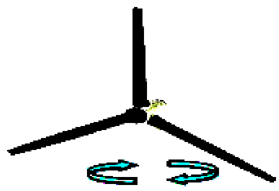

Fig. 6: Yaw Control [6]

There are three control systems used in horizontal wind turbines: first; control by Yaw and Tilt which is designed based on the tail feather theory and it is constantly responsible for turning the direction of the rotor to be oriented to the wind direction. Second, control by Pitch which alters the pitch of the blade in accordance to the speed of the wind to adjust the speed of the rotor, and third control by stall which progressively turns the rotor axis inside and outside the wind direction [4]. But when wind speeds are higher than the speed at which wind turbines operate, the blades change to a posture like they procrastinate and produce no lifting force. Therefore, it is necessary to know the relationship between the wind speed and the amount of energy produced by the wind turbines in order to determine the method of control required and to decide whether to continue working or stop it [6].

Fig. 7 shows the actual curve of the amount of energy extracted from the wind and determines the wind speed range at which the turbine begins to operate or shut down. It also shows that wind turbines operate within a limited range of wind speed. The wind speed at which the turbines are operating is called the start-up speed ("Cut-in"), and it is less than the speed at which the turbines cannot work for inefficient power production. The speed of the wind beyond which the turbines stop working is called the speed of cutting ("Cut-out") and this helps to protect the system from damage and collapse [5,6].

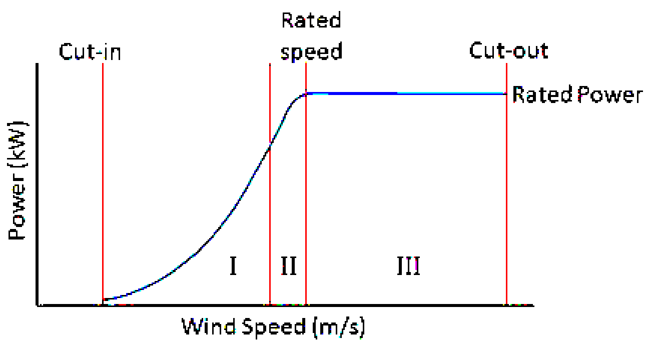

Fig. 7: Energy curve for a perfect wind turbine

Peter's law states that the maximum efficiency of any wind turbine, whatever their manufacturing, cannot reach or exceed 59 % in theory and it is called Power-Coefficient (C_p) [1]. The C*p* is a measure of the efficiency of wind turbines and it is a rate of the actual energy produced from the wind turbine to the total wind energy in both the blades of the turbine and the rotor at a limited wind speed [7]. Mathematically, the wind power in both the blades and the rotor of the wind turbine and the maximum output power of any wind turbine are represented by Equations 1 and 2, respectively [8].

$$P_w = 1/2\ \rho A v^3 \quad (1)$$

$$P_{wm} = 1/2\ \rho A v^3\ Cp \quad (2)$$

$$C_{pmax} = 0.59$$

Where:

"P_w" is the wind power on the turbine, "P_{wm}" the maximum output power of the wind turbine, "ρ" the air-density (kg/m^3), "v" air-velocity (m/s), "A" area sweeps by the wind turbine blades (m^2) and "C_p" is the power-coefficient.

III. MODELING AND SIMULATION

A. The system

In this study, a complete wind turbine system was set up using a software (PSCAD) program and Fig. 8 shows the block diagram of the simulation system for the wind turbine. This system *consists* of a wind turbine with a 190 rpm and two variable DC voltage sources to generate an output power of 19 kW. According to Equation 2, The maximum output power of the simulated system is

$C_p \times P_w = 0.59 \times 19 = 11.21\ KW.$

The DC sources are used to control the degree of deviation of the blade angle and to control the wind speed. The system is also containing a control circuit involving the multiplier and two sensors where they used to measure speed and torque of the rotor. The system was tuned with a mechanical load of 190 rpm by the drivetrain. Probes are used in the system to measure the voltage, current and power.

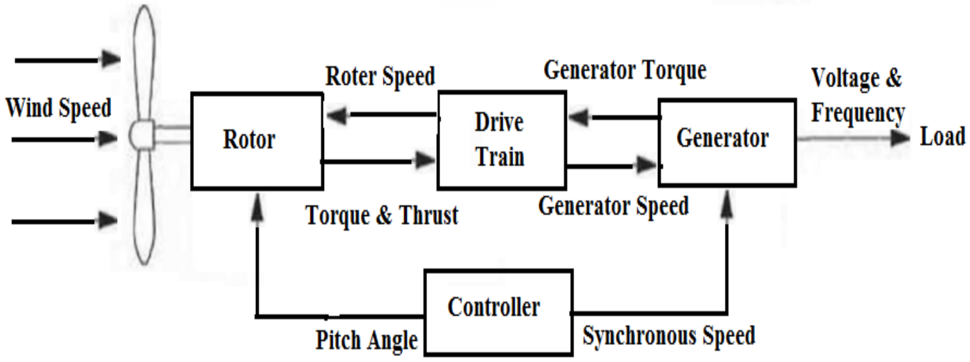

Fig. 8: The block diagram of the simulation system for the wind turbine.

B. Controlling and Operating Strategies.

Since the wind speed varies from time to time and from place to place, thus the simulated system was tested with several wind speeds. The most effective way to control the energy production of wind turbines is controlling the blade angle and the rotor speed. Therefore, the simulated system is operated according to these methods of control. The system was running for two different cases. Each case has different values of the wind speeds and angles of the blade which are increasing gradually by (1 m/s) and (± 0.5°) respectively as shown in Table 1.

TABLE 1. DETAILS OF TWO CASES USED TO RUN THE SIMULATED SYSTEM IN THE STUDY.

Blade Angle ±0.5°	**Output Power (Watt)**	**Wind Speed (m/s)**									
		0	1	2	3	4	5	6	7	8	9
0°	KW	0	0	0.08	0.2	0.3	0.5	0.7	1	1.2	1.3
0.5°	KW	0	0	0.1	0.3	0.4	0.6	0.8	1.9	2.2	2.8
-0.5°	W	0	0	0.02	0.04	0.06	0.05	0.28	0.42	0.54	0.63
1°	KW	0	0	0.1	0.2	0.9	1.9	3	5	6.8	8.5
-1°	W	0	0	0.01	0.03	0.04	0.13	0.24	0.37	0.49	0.58

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1.5°	KW	0	0	0.1	0.3	0.5	0.7	2.3	4	5.8	7
-1.5°	W	0	0	0	0.01	0.03	0.1	0.19	0.3	0.4	0.48
2°	KW	0	0	0.1	0.3	0.5	1	2	2.7	4.3	5.8
-2°	W	0	0	0	0	0.02	0.07	0.15	0.25	0.32	0.38
2.5°	KW	0	0	0.1	0.2	0.3	0.5	1	2.4	3.1	4.1
-2.5°	W	0	0	0	0	0.01	0.05	0.12	0.19	0.24	0.28

Blade Angle ±0.5°	***Output Power (Watt)***	***Wind Speed (m/s)***									
		10	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
0°	*KW*	*1.4*	*1.3*	*1.2*	*1*	*0.8*	*0.5*	*0.1*	*0*	*0*	*0*
0.5°	*KW*	*3*	*2.9*	*2.7*	*2.5*	*2*	*1.7*	*0.9*	*0.4*	*0*	*0*
-0.5°	*W*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
1°	*KW*	*9.8*	*10.5*	*10.8*	*10.8*	*10.5*	*10*	*9*	*8.2*	*7.6*	*7.2*
-1°	*W*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
1.5°	*KW*	*8.1*	*8.7*	*9*	*8.9*	*8.8*	*8.2*	*7.5*	*6.4*	*6.2*	*5.9*
-1.5°	*W*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
2°	*KW*	*6.3*	*7*	*7.1*	*7*	*6.8*	*6*	*5.3*	*4.8*	*4.2*	*4*
-2°	*W*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
2.5°	*KW*	*4.7*	*5*	*5*	*4.7*	*4.4*	*4*	*3.8*	*3*	*2.8*	*2.4*
-2.5°	*W*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

Blade Angle ±0.5°	**Output Power (Watt)**	**Wind Speed (m/s)**	
		20	21
0°	W	0	0
0.5°	KW	0	0
-0.5°	W	0	0
1°	KW	6.5	6
-1°	W	0	0
1.5°	KW	5.5	5
-1.5°	W	0	0
2°	KW	3.7	3.5
-2°	W	0	0
2.5°	KW	2.2	2.1
-2.5°	W	0	0

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IV. RESULTS AND DISCUSSION

The values of the output power for both cases are given in Table 1. The output power values of positive blade angles are for Case 1 and the values of negative blade angles are for Case2. The curves of these values are plotted in Fig. 9 and Fig. 10.

Case 1: It is obvious that the system works perfectly where it was no mechanical pressure on the blade and rotor of the wind turbine. In other words, there is no excessive increase in heat on the generator. The output power curves clarify that the system reaches its maximum output power (10.8 KW) at wind speed of (12 and 13) m/s and 1° angle of the blade as shown in Table 1 and Fig. 9. The comparison between the maximum

amount of energy produced by the simulation system and the maximum amount of energy calculated from Equation (1), (11.2) kW, shows that there is a very small difference in the amount which can be neglected. This means that there is a very small error ratio between theoretical and practical

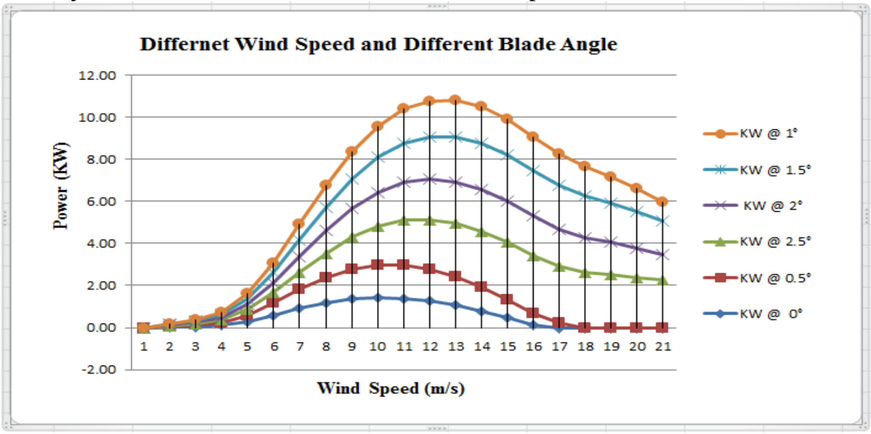

Fig. 9: Output curves for "Case 1".

Case 2: It seems from the output power curves in Fig.10 that the turbine works with non- acceptable blade angles. As a fact, the speed of the wind is non-controllable quantities. Therefore, the turbine performance in this case does not achieve the aim in generating power at all only fractions of watt which are equal approximately to zero as shown in Table 1. In fact, the data in Fig.10 indicate that the system was shutting down to protect the wind turbine from collapsing due to the compression disturbance of air pockets around the blade which causes a high mechanical pressure on the blades and the rotor.

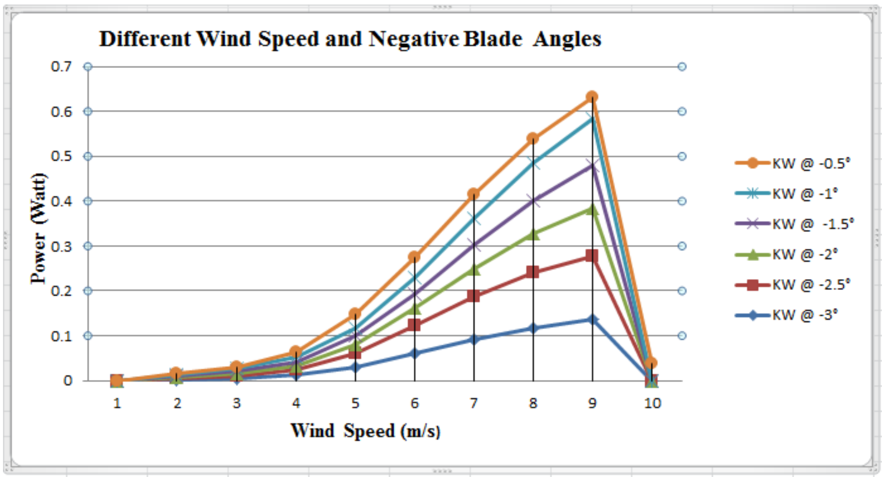

Fig 10: The output power curves for the "Case 2".

V. CONCLUSION

The simulation of the model was successful; Fig.1 and 2 illustrate the simulation results, by analyzing the results it was concluded that changing the pitch angle of the blades was affected at different wind speeds. The assumption was that with the wind speed increasing, the optimum angle would be reduced. In the simulation I found that the optimal angle is not fixed. When the wind speeds were (12 and 13) m/s the output power was 10.8 KW and the optimal pitch-angle was 1° angle. Fig.2 indicates that when the speed of the wind is more than around (12-13) m/s the protection system of the wind turbine will work to keep the components of the wind turbines from being damaged. Thus, in the case of a storm, the protection system turns the angle of the blade to a degree where the lifting force is zero. This leads to a halt in the production of energy, removes the mechanical pressure on the blades and protects the generator from high temperature due to excessive electrical load. Once stopped, the turbine must be re-operated after the storm calm.

Finally, if the angle of the blade is "too large or too small", the wind turbines may not start spinning at low or high wind speeds as experienced in the study. Therefore the recommendations to improve the performance of the horizontal wind turbine are:

1. Using larger fans that have more speed settings than three in order to work with faster wind speeds.
2. Using wind generator with improved pitch size in order to find the best approximation of the optimal blade angle.

The output power of the wind turbine can be maximized by manipulating the blade deflection angle of the turbine to match the speed and direction of the wind.

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