An Experimental Investigation of Various Impacts on the Performance of A Small-Scale Upwind HAWT

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***Abstract*— The power production by wind turbines usually falls below the theoretical maximum power coefficient of the Betz limit of 59.26%. This is mainly related to the unsteady aerodynamic environment and poor wind turbine design systems. In this paper, an experimental study is carried out on a small-scale upwind horizontal axis wind turbine (HAWT) to discuss the aspects of better design systems and to investigate the influence of the rotor blades number, and the variation in the wind speed and its direction on the wind turbine performance. To achieve this aim, three different rotors of the same size with 2, 3, and 4 blades have been fabricated and tested experimentally to evaluate the optimum blades number at various unsteady operating conditions. In this study, it is found that the power extraction of the wind turbine increases by increasing the blades number of the rotor and the wind speed, while it decreases by increasing the yaw angle. Indeed, it is also shown that a good wind turbine design can even exceed the maximum power coefficient of the Betz limit (16/27). The present work can be considered as an important step for understanding various impacts on the performance of wind turbines, which could help to select/deign better wind turbine design systems.**

***Key Words*—small-scale upwind HAWT, wind speed, yaw angle, rotor blades number.**

I. INTRODUCTION

WIND turbines are built to extract kinetic energy from the wind and convert it to electrical energy. Horizontal axis wind turbines are the most common devices because of their high efficiencies as their blades always move perpendicularly to the wind, extracting the power from the wind through the whole rotor rotation. These blades are mounted on the rotor hub, which is connected with the turbine nacelle by the low-speed shaft. These are set on the turbine tower. The HAWTs can be upwind (the rotor is upstream of the tower) or downwind (the rotor is downstream of the tower) turbines [1]. Extraction of the kinetic energy in the wind depends on the design of wind turbines. This extracted energy is a function of the reduction in the wind speed that passes through the swept area of the wind turbine. Indeed, it is still not possible to utilise all the available kinetic energy through the rotor swept area as this implies zero velocity behind the wind turbine [2][3]. It was shown by the German physicist Albert Betz in 1919 that efficiency of wind turbine cannot exceed 16/27 or 59.3% of the kinetic energy in the wind. This factor is known as Betz's coefficient or power coefficient C_p, where the maximum $C_p = 0.593$ is called Betz limit [4]. In this theory, it is assumed that the influences of wake rotation, drag, and vortex shedding are ignored, but in reality, these lead to further losses in the turbine efficiency[2][4]. The tip speed ratio is an important design parameter for wind turbines. Selecting the suitable tip speed ratio should take into account some aerodynamic aspects such as efficiency, torque, mechanical stress, aerodynamics and noise. A high tip speed ratio increases the turbine efficiency [2][5] but noise, aerodynamic and centrifugal stresses are also increased, which lead to blade failure and shorten the life time of the wind turbine [2][6]. The practical tip speed ratios for modern horizontal axis wind turbines, that produce efficient electrical energy, are 9-10 for two-bladed rotor and 6-9 for three-bladed rotor [7]. There are various theories used to determine the optimum chord length of the wind turbine blade [2][5][7][8]. The simplest approach to calculate the chord length is by the use of the Blade Element Momentum (BEM) theory [9] based on Betz limit, local wind velocity and aerofoil lift force coefficient. A major disadvantage of these methods is that wake and drag losses are negligible. Therefore, for better accuracy, more advanced optimization methods need to be improved and utilized [8][10][11]. Another fundamental consideration is the aerodynamic performance for efficient rotor design [12]. An appropriate design approach needs to maximize the lift force coefficient of the aerofoil section, given that it is responsible for the power yield of the wind turbine. The drag force coefficient, on the other hand, needs to be minimized as it acts in the opposite direction to the blade motion, creating friction or resistance [12][13].

This paper presents an experimental study performed on three small-scale wind turbines with 2, 3, and 4 blades. The

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turbines were made of the same size to have fair comparisons between their performances. The main purpose is to investigate the following:

- The influence of the change in the wind speeds and their directions on the performance of the wind turbines having different number of rotor blades.
- The impact of the rotor blades number on the performance of the wind turbines, and to evaluate the optimum blades number with respect to the design tip speed ratio, material cost, and lift time of the wind turbine.
- The aspects of having a perfect wind turbine design.

II. EXPERIMENTAL PROCEDURE & TEST FACILITIES

This section presents details of the designed and fabricated wind turbines and the selected test conditions along with description of the used instrumentation and the measurement technique.

A. Reference Wind Turbines and Test Facilities

Three different small-scale upwind horizontal axis wind turbines with 2, 3, and 4 blades of the same size were fabricated and tested as shown in Figure (1). The blade dimensions of each individual turbine are given in Table I and Figure (2).

The hub diameter and blade length are 0.075 m and 0.24 m respectively. All tests were carried out at a fixed pitch angle of 0^0. At each wind speed, the wind turbines were tested experimentally under various yaw angles of 0^0, 18^0, and 30^0.

TABLE I: THE BLADE DIMENSIONS OF THE TESTED WIND TURBINES.

r/R (-)	r (m)	Chord (m)	Twist (deg)	Thickness (m)
0.1	0.024	0.037	34.0	0.002
0.2	0.048	0.042	21.0	0.002
0.3	0.072	0.038	15.2	0.002
0.4	0.096	0.034	9.90	0.002
0.5	0.12	0.03	8.60	0.002
0.6	0.144	0.026	7.30	0.002
0.7	0.168	0.023	6.10	0.002
0.8	0.192	0.019	4.80	0.002
0.9	0.216	0.015	3.60	0.002
1	0.24	0.004	3.60	0.002

B. Measurements and Instrumentation

1. The wind turbines were tested in a wind tunnel at wind speeds of 2.6, 3.8, and 5 m/s, measured by a propeller type digital anemometer placed at the turbine hub height.
2. The turbine rotor rotations were measured by a laser tachometer. In this method, a focused light beam is directed onto the rotating shaft with a thin reflected mark attached to it. The result of the mechanical measurement of speed is displayed on a 5-digit LCD.
3. The torque exerted on the rotating shaft of the wind turbine was measured by the use of rope brake dynamometer technique as illustrated in Figure 3. In this technique, the following steps were applied:

- Two pulleys were used in this measurement. Smooth break pulley is connected with the turbine shaft and rotates with it and the other is positioned at a distance from the turbine (see Figure 3). The latter rotates freely to increase the accuracy of the measurements.
- A rope is connected with a spring balance (weight reading) and known weights. This rope passes through the two pulleys mentioned above.
- The turbine is first made to rotate at a constant speed without weight to obtain the maximum rotor rotation.
- A known weight (W_1) is then added as seen from Figure 3. The range of the known weights is from 10 g to 50 g. The frictional force (W_2) on the break pulley is taken from a spring balance reading.
- From the measured values, the angular velocity (ω), mechanical torque (T), mechanical power (P) and power coefficient (C_p) for each turbine are determined as follows:

$$\omega = 2\pi N / 60 \quad (1)$$

$$T = (W_2 - W_1) \times g \times r_p \quad (2)$$

$$P = T \times \omega \quad (3)$$

$$C_p = \frac{P}{1/2 \rho A U_\infty^3} \quad (4)$$

where N is the rotational speed (*rpm*), g is the gravity (m/s^2), r_p is the radius of the break pulley (*m*), ρ is the air density (kg/m^3), A is the rotor rotational area (m^2), and U_∞ is the wind speed (*m/s*).

Fig. 1.Three different fabricated small-scale upwind horizontal axis wind turbines for experimental tests: (a) 2-bladed rotor. (b) 3-bladed rotor. (c) 4-bladed rotor.

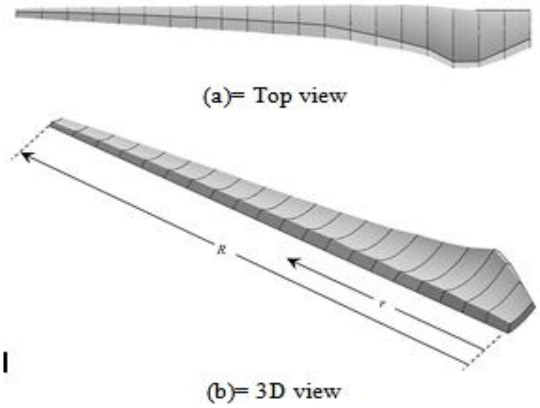

Fig. 2: The geometry of the wind turbine blade.

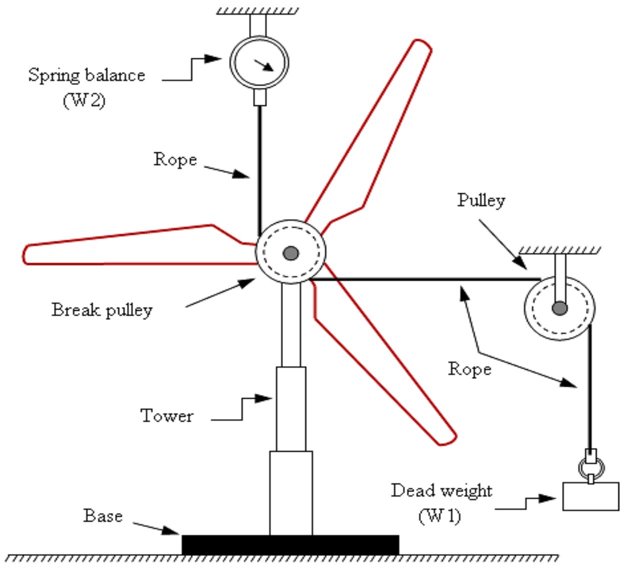

Fig. 3: Rope brake dynamometer to measure torque.

III. RESULTS AND DISCUSSION

This section will present various comparisons between the experimental results of the small-scale upwind horizontal wind turbines with 2, 3 and 4 blades at wind speeds of 2.6, 3.8, and 5 m/s at yaw angles of 0^0, 18^0, and 30^0.

Table II and Figure (4) present the measured torques, powers, and power coefficients of the two-bladed rotor at different wind speeds and yaw angles. It can be observed that with increasing wind speed, the mechanical power output increases. That is because the available power in the wind ($1/2\rho AU_\infty^3$) is proportional to the cube of wind speed. The same observation can also be seen in the measured torques, powers, and power coefficients of the three-bladed and four-bladed rotors illustrated in Tables III and IV and Figures (5 and 6). It can also be noted that the performance of the two-bladed rotor is the lowest because the spaces between the blades are large and so, most of the wind passes without extracting more kinetic energy by the blades.

In all test cases, with the increase in the yaw angle from 0^0 to 18^0, and to 30^0, the power output decreases due to the impacts of: (1)- high angles of attack, experienced by the blades, (2)- unsteady dynamic stall vortex on the blades, and (3)- unsteady wake just behind the rotor, which could influence on the flow field that passes through the rotor swept area from 2 up to 5 rotor diameters. These phenomena become unstable and significant under yawed flow conditions, leading to a reduction in the power. This was already established in the work of Elgammi and Sant [14].

The blades number has a dramatic impact on the performance of the wind turbines as depicted from Tables (II-IV) and Figures (4-6). The two-bladed rotor (see Table II and Figure (4)) has the lowest power outputs, while these for the four-bladed rotor (see Table IV and Figure (6)) are the highest. Therefore, it could be understood that higher blades number means that the flow area on the rotor blades becomes larger and so, more power can be extracted from the wind. However, it should be noted that the three-bladed rotor (see Table III and Figure (5) is the best choice among the other because of that the two-blade rotor needs to rotate fast generating a high noise, whereas the four-blade rotor requires more materials and thicker shaft than the other rotors due to stresses. The measured mechanical power is increased from 3.6% to 15% when comparing the performance of the three-bladed rotor with the two-bladed rotor and the four-bladed rotor with the three-bladed rotor respectively. Taking into account the cost of the material and construction, it is obvious that the turbine with three blades is the optimal and economical one.

To investigate the influence of rotation on the performance of the wind turbines, the wind speeds were changed from 2.6, 3.8, to 5 m/s as given in Tables (II-IV) and Figures (4-6). For all test cases, the increase in the wind speeds, yields to increasing of the rotor rotations. Based on these results, high rotor rotations are not an advantage. This is clear from the power coefficients in Tables (II-IV) and Figures (4-6), where they are decreased rapidly with increasing the rotor rotations. The main reasons behind this are: (1)- the tip speed ratio ($\lambda = R\omega/U_\infty$) of the design and fabricated small-scale upwind horizontal wind turbines is 4, which corresponds to wind speed of 2.6 m/s. Therefore, the best performance is obtained at this design tip speed ratio, and (2)- when this small-scale upwind horizontal wind turbine rotates fast, the rotor area becomes like a solid disc, not allowing enough wind to pass through the gaps between the blades, and subsequently, the blades could not extract the kinetic energy from the wind more efficiently.

An interesting feature of the design wind turbine in this paper is that the Betz limit of 59.26% (see the introduction section for more details) is exceeded by the three- and -four blades rotors. As seen from Tables (II-IV) and Figures (4-6), the turbine with three and four blades achieved more than 59.26% of the kinetic energy in wind at the design tip speed ratio of 4. The maximum captured kinetic energy from the wind is 64% for the three-bladed rotor, while that for the turbine with four blades is 68%. In fact, this is mainly related to the perfect and accurate design. In the current design, the balance is greatly achieved, where the weights of the blades and the distance from the blade tip to another are exactly the same. The total weight and the used materials in present design are light and flexible. Typically, these would improve the performance of the wind turbine as the friction forces between the stationary and rotating parts are reduced.

TABLE II: MEASURED PERFORMANCE OF THE TWO-BLADED ROTOR AT DIFFERENT WIND SPEEDS AND YAW ANGLES.

	Yaw=0^0			Yaw=18^0			Yaw=30^0		
U_∞ (m/s)	2.6	3.8	5	2.6	3.8	5	2.6	3.8	5
N (rpm)	360	419	452	300	371	410	260	337	337
ω (rad/s)	37.69	43.87	47.33	31.41	38.85	42.93	27.22	35.29	40.10
T (N.m)	0.036	0.049	0.053	0.035	0.039	0.049	0.029	0.036	0.040
P (Watt)	1.387	2.151	2.553	1.116	1.524	2.105	0. 801	1.298	1.622
C_p (-)	0.532	0.264	0.137	0. 428	0.187	0.113	0.307	0.159	0.087

TABLE III: MEASURED PERFORMANCE OF THE THREE-BLADED ROTOR AT DIFFERENT WIND SPEEDS AND YAW ANGLES.

	Yaw=0^0			Yaw=18^0			Yaw=30^0		
U_∞ (m/s)	2.6	3.8	5	2.6	3.8	5	2.6	3.8	5
N (rpm)	382	433	463	340	416	448	310	371	410
ω (rad/s)	40.00	45.34	48.48	35.60	43.56	46.91	32.46	38.85	42.93
T (N.m)	0.041	0.051	0.056	0.039	0.042	0.051	0.034	0.039	0.044
P (Watt)	1.667	2.335	2.734	1.396	1.869	2.415	1.115	1.524	1.895
C_p (-)	0.640	0.28	0.147	0.536	0.229	0.130	0.428	0.187	0.102

TABLE IV: MEASURED PERFORMANCE OF THE FOUR-BLADED ROTOR AT DIFFERENT WIND SPEEDS AND YAW ANGLES.

	Yaw=0^0			Yaw=18^0			Yaw=30^0		
U_∞ (m/s)	2.6	3.8	5	2.6	3.8	5	2.6	3.8	5
N (rpm)	366	424	460	335	391	425	272	350	380
ω (rad/s)	38.22	44.40	48.17	35.08	40.94	44.50	28.48	36.65	39.79
T (N.m)	0.046	0.053	0.057	0.041	0.046	0.055	0.039	0.044	0.049
P (Watt)	1.780	2.395	2.776	1.462	1.907	2.455	1.117	1.617	1.951
C_p (-)	0.683	0.294	0.149	0.561	0.234	0.132	0.428	0.198	0.105

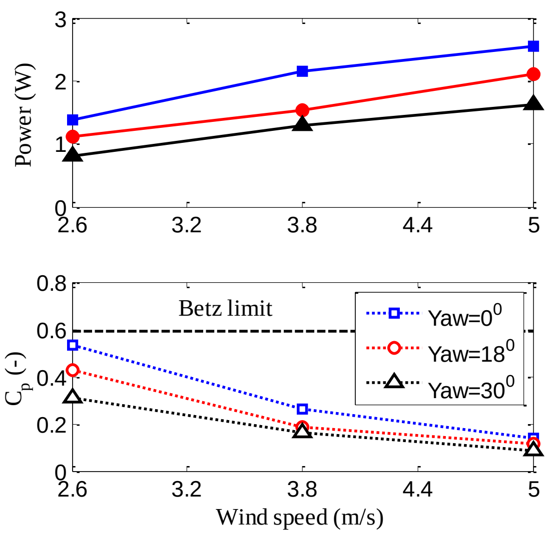

Fig. 4: Performance of the Two-bladed rotor.

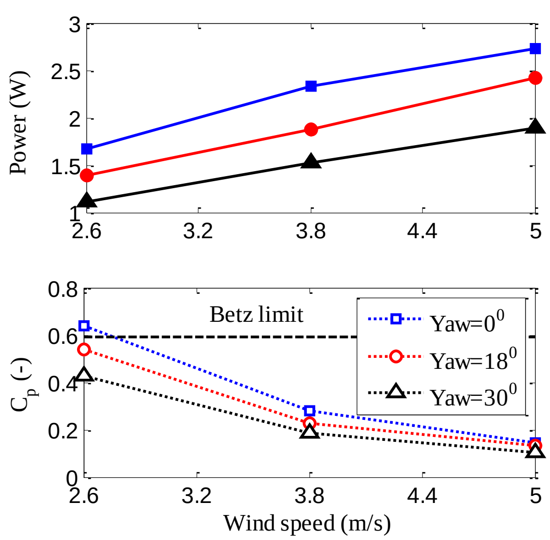

Fig. 5: Performance of the Three-bladed rotor.

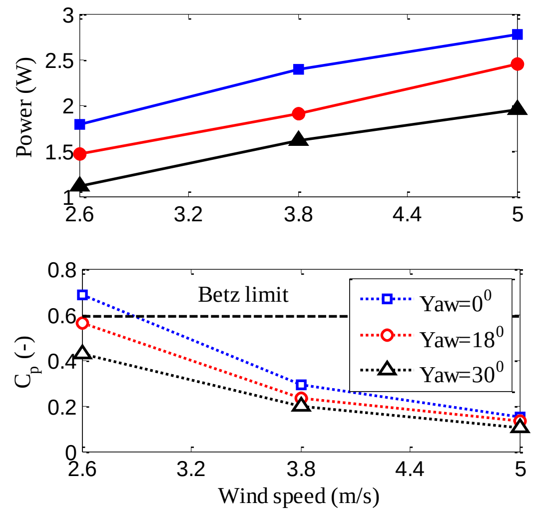

Fig. 6: Performance of the Four-bladed rotor.

IV. CONCLUSION

This paper presents an experimental study conducted on three small-scale upwind horizontal wind turbines with 2, 3, and 4 blades of the same size. The influences of wind speeds and yaw angles were studies and addressed. The impact of the rotor blades number on the performance of the wind turbines has been highlighted and understood. From this study conclusions are addressed as follows:

1) The increase in the wind speed leads to increasing of the rotor rotation and the power output because the wind power is proportional to the cube of the wind speed. However, very high rotor rotations are not always an advantage for wind turbines as they usually yield to high noise and stresses near the root sections of the wind turbine blade, resulting in fatigue. Wind turbines should always operate at their design tip speed ratios.
2) The influence of yaw angle or wind direction is very important when constructing a wind farm. Under yawed flow conditions, the extracted power is reduced due to the significant impacts which come from the presence of the unsteady dynamic stall on the blades and the unsteady wake just behind the turbine rotor. Therefore, wind turbines should operate with a yaw drive to keep the rotor facing into the wind (axial flow direction) as the wind direction changes.
3) It is known that more blades would increase the flow area and therefore, the extracted kinetic energy from the wind. However, a multi-bladed turbine (>3) is expensive as it requires more materials and is difficult to construct due to the heavy weight. Indeed, a rotor with many blades becomes impractical if it rotates fast. This is because the flow through the rotor swept area will be almost blocked. It was shown in this paper that a turbine with three blades achieves the balance between the turbines with two and four blades in terms of the extracted power, rotor rotation, and cost.
4) Although the Betz's law indicates that no turbine is able to

extract more than 59.26% of the kinetic energy in the wind, the present paper proves that a perfect wind turbine design can even exceed that limit. Manufacturer should make sure that a suitable wind turbine should be light with a great balance between the wind turbine components. The weight of the turbine blades and the distance from the blade tip to another should be calculated and perfectly matched to achieve the best performance.

REFERENCES

[1] Manwell, F., McGowan, J. and Rogers, A. (2003). *Wind Energy Explained -Theory, Design and Application*. John Wiley and Sons Ltd.

[2] Gasch, R. and Twele, J. (2002). *Wind Power Plants: fundamentals, design, construction and operation*. Solarpraxis: Berlin, Germany.

[3] Gorban, A., Gorlov, A. and Silantyev, V. (2001). 'Limits of the turbine efficiency for free fluid flow', *J. Energy Resour. Technol. Trans.*, 123(4), p.311.

[4] Burton, T. (2011). *Wind Energy Handbook*. John Wiley and Sons Ltd.: Chichester, UK.

[5] Duquette, M. and Visser, K. (2003). 'Numerical implications of solidity and blade number on rotor performance of horizontal-axis wind turbines', *J. Sol. Energy Eng.* 125(2), p.425.

[6] Oerlemans, S., Sijtsma, P. and Lopez, B. (2006). 'Location and quantification of noise sources on a wind turbine', *J. Sound Vib.*, 299, pp.869–883.

[7] Hau, E. (2006). *Wind Turbines, Fundamentals, Technologies, Application, Economics*. 2nd ed., Springer: Berlin, Germany.

[8] Chattot, J. (2003). 'Optimization of Wind Turbines Using Helicoidal Vortex Model', *J. Sol. Energy Eng.*, 125(2), p.418.

[9] Khaled, M., Ibrahim, M., Abdel Hamed, H., and Abdel-Gawad, A. (2007). 'Aerodynamic Design and Blade Angle Analysis of a Small Horizontal–Axis Wind Turbine', *American Journal of Modern Energy*, 3(2), pp. 23–37.

[10] Fuglsang, P. and Madsen, H.A. (1999). 'Optimization method for wind turbine rotors', *J. Wind Eng. Ind. Aerodyn.*, 80(1-2), pp.191–206.

[11] Jureczko, M., Pawlak, M. and Mezyk, A. (2005). 'Optimisation of wind turbine blades', *J. Mater. Proc. Technol.*, 167(2-3), pp.463–471.

[12] Maalawi, K. and Badr, M. (2003). 'A practical approach for selecting optimum wind rotors. *Renew*', *Energy*, (28), pp.803–822.

[13] Griffiths, R.T. (1977). 'The effect of aerofoil characteristics on windmill performance', *Aeronaut. J.*, (81), pp.322–326.

[14] Elgammi, M. and Sant, T. (2016). 'Combining Unsteady Blade Pressure Measurements and a Free-Wake Vortex Model to Investigate the Cycle-to-Cycle Variations in Wind Turbine Aerodynamic Blade Loads in Yaw', *Energies*, 9(6), p.460.